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Discharge-Suspended Sediment Relationships in the Mississippi-Atchafalaya Rivers System, Louisiana.

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DISCHARGE-SUSPENDED SEDIMENT RELATIONSHIPS IN THE MISSISSIPPI-ATCHAFALAYA RIVER SYSTEM, LOUISIANA

A Dissertation

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by

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LIST OF ABBREVIATIONS AND CONVERSION FACTORS

Q:	discharge (volumetric streamflow rate)
Qs:	suspended sediment discharge or load
cfs:	cubic feet per second
M:	mass
T:	time
L:	length
t:	tons
AHP:	above the Head of Passes
d_x:	particle size at which x% of sediments are finer by weight
log:	logarithm to the base 10
m.s.l.:	mean sea level
lg.:	landing

U.S. Customary Units of measurement used in this dissertation can be converted to metric (SI) as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
miles	1.609344	kilometers
square miles	2.589988	square kilometers
pounds	0.4535924	kilograms
tons	0.9071847	metric tonnes
cubic feet per second	0.02831685	cubic meters per second

ABSTRACT

Although suspension is the dominant mode of material transport in rivers world-wide, concepts of suspended sediment transport have come mostly from studies of small rivers. This study describes relationships between discharge and suspended sediment in a large river system, the Mississippi-Atchafalaya in south Louisiana. The primary objectives are: 1) to determine whether the suspended silt-clay and sand follow different relationships with discharge because the silt-clay is supplied largely from the basin whereas the sand is supplied largely from the channel perimeter; and 2) to determine whether hysteresis effects differ in high as compared to low discharge years because of conditions including supply limitations and bankfull flows.

Empirical relationships of discharge with suspended sediment, silt-clay, and, to a lesser extent, other variables in the Mississippi, Atchafalaya, and Old rivers show quadratic log-log relationships, while the Red River shows linear log-log relationships. The nonlinearity is strongest in the fine sediments and reflects the decreased availability of fine material at high discharges possibly related to the basin's climate, dams, and revetments, and removal of sediments by flushing. Further downstream in the Mississippi, velocities decrease at low discharges, fine material becomes increasingly abundant, and settling and resuspension of fines become more important processes.

The Mississippi, Atchafalaya, and Old rivers show pronounced hysteresis effects with a lead of sediment peaks before discharge crests of as much as two months during high discharge years. The lead decreases with decreasing discharge maxima so that in low discharge years sediment peaks and discharge crests coincide. Even though in all years the Red's discharge is less than that contributed through Old River, time series show that the Atchafalaya's sediment signature, which shows numerous sediment peaks during falling and stationary discharges, is strongly influenced by the sediment-laden Red River in most years. Results show the need for further study of large rivers and that existing concepts regarding relationships of basin size and hysteresis effects, as well as the relative downstream movement of sediment waves and floodwaves should be reassessed.

INTRODUCTION

In most of the world's large rivers, suspension is the major mechanism of material transport (Walling, 1985). The suspended load, including wash load (silt and clay particles ($\leq$ 0.062 mm) finer than those typically found on the bed and moving readily in suspension) and the suspended bed material load (sand and coarser particles (> 0.062 mm) typically found on the bed that are transported and maintained in the water column by turbulent mixing processes), makes up about 70 to 78% of the world-wide material transport (Holeman, 1968; Milliman and Meade, 1983; Walling, 1985b). The dissolved load consists of material in solution and is estimated as 14 to 22% (Meybeck, 1976) of the total material transport (Holeman, 1968; Milliman and Meade, 1983), although in the major rivers of the world it ranges from 3 to over 90% locally, depending on the basin's relief and climate (Meybeck, 1976). The remainder is transported as bed load, which is generally coarse and moves by saltation, sliding, or rolling at velocities less than those of the surrounding flow. Bed load comprises less than 10% of the total sediment transport world-wide though higher proportions of bed load are often reported elsewhere, such as in mountain streams (Walling, 1985b; Lewin, 1985).

Suspended sediment transport is poorly understood, despite the significant advancements in knowledge made in this century (Vanoni, 1975). While the bed load is difficult to measure, the great majority of sediment transport equations concern only the bed material load or coarse particle transport (bed load and suspended bed material load combined), which generally constitutes a smaller fraction of the total sediment load than the wash load (Simons and Senturk, 1977). The total sediment load can be predicted only if the wash load, or fine particle transport, is estimated by measurement, empirically, or by analytical relations (Simons and Senturk, 1977). These approaches are important for understanding sediment transport because in many rivers wash load is the dominant component of the suspended sediment and the total sediment load.

Furthermore, most studies of sediment transport relationships have been conducted in small rivers, and many of the relationships and concepts about sediment transport in rivers have been derived from these studies. However, it is possible that large rivers operate very differently than small rivers in some respects and that the existing concepts and relationships in small rivers, therefore, may not apply to large ones. Investigations of large rivers with substantial and long-term data bases are needed to broaden our understanding of sediment transport in rivers.

The purpose of this study is to analyze relationships between discharge and suspended sediment using a descriptive approach in one large river system, the Mississippi-Atchafalaya of south Louisiana. This system is an ideal study area because it possesses perhaps the best suspended sediment data base among the world's large rivers. Unlike most previous studies, the fine and coarse components in suspension are examined individually and in combination. The results contribute to current understanding of suspended sediment transport and the behavior of different size fractions in large river systems through description of empirical relationships and some physical phenomena.

Differences between fine and coarse material transport in suspension

The size of material in suspension is one of the important properties that determines the entrainment, transportation, and subsequent deposition of sediment (Vanoni, 1975). Sediment size is typically divided into two broad classes, the fine and coarse material, which at times are in suspension and at other times are found on the bed. In most rivers, the fine material or wash load is continually in suspension, whereas the coarse material travels in suspension intermittently.

The finer suspended material or wash load is supplied to rivers by hillslope erosion by processes such as rainsplash and sheetwash, and by bank erosion, with fine material being sheared off by the flow or thrown in suspension after bank collapse (Knighton, 1984; Walling, 1985). Factors important in determining sediment yield, and wash load in particular, include precipitation and runoff characteristics, soil resistance, basin topography, and the nature of the plant cover (Knighton, 1984;

Hadley et al., 1985). The rate of wash load transport is largely determined by its rate of supply from the drainage basin rather than the transport capacity of the stream. Wash load is relatively uniform throughout the stream cross section, moves in suspension at approximately the same speed as the flow, and settles out where flow velocities are reduced below the entrainment velocities. Wash load transport often peaks early in a flood while rain and surface runoff are still occurring (Einstein et al., 1940; Richards, 1982), a process commonly described as flushing. Streams carrying predominantly wash load are typically narrower and deeper than those carrying coarser materials (Schumm, 1960).

Most of the coarser particles in suspension are drawn from the bed and channel perimeter (Walling, 1985), and show vertical variations in the cross sections of most streams (Colby, 1963; Fisk, 1952; Wells, 1980; Richards, 1982). Unlike the wash load, the suspended bed material load is largely determined by the transporting capacity of the flow (Graf, 1971; Walling, 1985), but may also show greater contributions early in the flood event because the rising water level may introduce new sources of sediment that are reduced by the time the flood recedes (Carson et al., 1973; Bogen, 1980; Richards, 1982). Many variables are involved in bed material transport (Table 1) whose independence or dependence cannot always be determined as simple cause and effect (Knighton, 1984), because physically meaningful linear relations cannot be found. The bed material load is typically somewhat discontinuous, and changes transport modes with increasing flow intensity, with uninterrupted suspension being on the upper end of the continuum (Abbott and Francis, 1977; Leeder, 1979). The sediment contribution from local channel bed and bank sources, as opposed to non-channel sources, generally increases in the downstream part of drainage basins where slopes are less steep (Griffiths, 1979; Knighton, 1984). A larger bed-material load requires wide and shallow cross-sections in which great shear stresses are directed against the bed and enable the stream to transport the coarser load.

<u>Empirical relationships of suspended sediment and discharge</u>

Sediment transport in a stream depends on such a variety of circumstances that it is impractical to define fixed laws for the rate and amount of sediment transport in streams at any

Table 1. Variables pertinent to bed material transport (sources include Vanoni, 1975; Knighton, 1984; and Naden, 1988).

Flow properties	Fluid properties	Sediment properties	Other properties
Discharge	Kinematic viscosity	Density	Gravity
Velocity	Density	Size	Planform geometry
Flow depth	Temperature	Sorting	Cross-sectional shape
Width	Sediment concentration	Shape	Obstacles
Slope		Fall velocity	
Resistance		Protrusion into flow	
Shear stress		Packing	
		Imbrication	

specific location (Guy, 1964). Existing laws or theoretical studies are based largely on assumptions of quasi-steady and quasi-uniform flow, assumptions which are uncharacteristic of natural streams (Allen, 1974). Consequently, most of the recent work on relationships between suspended sediment and hydraulic parameters is based on the empirical approach and utilizes simple statistical techniques.

Empirical relationships between suspended sediment and discharge have been based on log-log transformations at least since the initial work of Campbell and Bauder (1940). They found good relationships between suspended sediment load and discharge. Discharge is a composite of the velocity, depth, and width, of which the velocity and depth also have been widely used in theoretical relationships of sediment and hydraulic parameters (e.g. Graf, 1971). Furthermore, discharge is available in reports of many agencies and organizations, whereas velocity and depth are generally not published.

Walling (1974) suggested that the examination of power functions or log-log relationships between sediment concentration and discharge could be more meaningful than log-log relationships between sediment load and discharge. Sediment load is computed from discharge and concentration, and the load-discharge regressions would therefore have discharge as a factor in both sides of the equation. However, many workers, unaware of the statistical errors caused by regressing sediment load with discharge, are still comparing these two parameters.

Discharge in most instances has been shown to correlate fairly well with sediment load, sediment concentration, and mean sediment size (Wood, 1977). The relationships are typically linear although appreciable scatter may be present. Scatter in discharge-sediment relationships is produced by variations in the flood peak magnitude, antecedent moisture conditions, season and water temperature, bank failures, supply limitations, varying patterns of tributary inflow, land cover, land use, dredging, and other dynamic and non-stationary parameters in the system, plus errors in the field and laboratory measurements (Guy, 1964; Walling and Gregory, 1970; Walling and Teed, 1971; Porterfield, 1972; Allen, 1974; Walling, 1977).

Some empirical relationships are markedly nonlinear and concentrations may either increase more slowly, or more rapidly, above a critical discharge. The former may be explained by the limitation of sediment supply from the catchment, even where the flow is increasing, whereas the latter probably reflects the expansion of partial area contributing to the sediment supply (Petts and Foster, 1985). Alternative relationships that have been applied include the use of rating curves only for discharge observations above a certain threshold (Campbell and Bauder, 1940), dog leg, jackknife, or multiple curves applied to different discharge ranges (Anderson, 1954; Gregory and Walling, 1973; Miller, 1988), multivariate relationships (Colby, 1956; Abraham, 1969; Walling, 1977a) and simple quadratic functions (Bennett and Sabol, 1973).

A few researchers including Church (1967) and Richards (1973) have suggested some causes for nonlinearity in other types of hydraulic and geomorphic data, including changes of roughness and channel geometry with discharge, that may also be prominent causes for nonlinearity in discharge-suspended sediment relationships. Richards (1973) applied a quadratic log-log function in his study of hydraulic geometry, and suggested that it was possible that sediment data would follow such functions also. The physical explanation for the nonlinearity of these relationships was attributed to hydraulic, geomorphic, and sedimentologic factors. Hydraulic discontinuities may be a result of the change from lower to upper regimes of flow, which produces attendant changes in sediment transport, bedforms, and roughness. Geomorphic discontinuities include the change from below- to above-bankfull flow conditions. Sedimentologic discontinuities include the decline of supply of specific sizes of material available for transport. Combinations of these conditions may cause highly complex nonlinear relationships. Intuitively, sediment transport would be affected by these discontinuities, and should also show nonlinearity with discharge if a wide discharge range were sampled.

One of the factors that inhibits advancements in understanding fluvial sediment transport is that most studies are largely concerned with the behavior of the coarse fraction or the total transport, with little attention directed toward the fine cohesive component (Wolman, 1977). The wash load is largely supply-based (Walling, 1985), which may be a reason for this lack of attention, and several studies have found (Colby, 1963) or enforced (Graf, 1971; Knighton, 1984; Komar, 1988) the viewpoint that the fine material in suspension (wash load) shows no well-defined relation with discharge. While the wash load may not exhibit a clear functional relationship with the flow rate, there is a need for more extensive work with the silt-clay and sand components of suspended sediment than has been conducted to-date.

Further work with the silt-clay component is important because: 1) in many rivers, fine material is the dominant component of the suspended load; 2) even if it is not the dominant component, the wash load may control the function of the discharge-suspended sediment relationship (e.g. Gregory and Walling, 1973); 3) in some areas, input of fine material from the channel perimeter may be significant; and 4) the relationships of the wash load with discharge have not been widely tested and deserve at least the same amount of attention as other supply-based parameters such as dissolved load. If particle size data are available, the distinction between the fine (silt-clay) material and coarse (sand) material in suspension can easily be made and their relationships to other hydraulic parameters can be assessed. Despite the fact that such data are measured and published by many agencies, particularly for many rivers in the United States, few studies have examined these separately.

Hysteresis

Directly related to the dependence of wash load on supply (Walling, 1985) or bed material load on supply (Carson et al., 1973; Bogen, 1980) is the phenomenon of hysteresis. Hysteresis occurs when the dependent variable shows different values according to whether the independent variable is decreasing or increasing, such that a bivariate plot shows a looped form. Both clockwise and counterclockwise hysteresis loops have been described for relationships between suspended sediment[1] and discharge, although the relationships between discharge and concentration may be more complex than a simple lead, lag, or synchronism if graphed on a bivariate plot. Single hydrologic events on bivariate plots have more recently been grouped into five classes, differentiated on the basis of mode, spread, and skewness in a nondimensional way (Williams, 1989). If a discharge event is complex, showing multiple rises and falls before cresting, a much greater number of responses are possible (Wood, 1977; Olive and Reiger, 1984; Pickup, 1988).

Hysteresis is a common phenomenon in discharge-suspended sediment relationships, yet opinions concerning its cause are divided. When the sediment peak occurs well before the hydrograph peak, it is attributed to a progressive reduction in the availability of sediment for mobilization and transport. This reduction may be manifest during an individual event, where maxima of sediment concentration and loads will occur before the hydrograph peak, or during a closely spaced sequence of flood events where sediment will show a progressive decrease with similar levels of water discharge. Regions where suspended sediment has been observed to lead the water discharge include the Enoree River in South Carolina (Einstein et al., 1940), the East Fork of the Deep River in North Carolina (Johnson, 1943), the San Juan River (Leopold et al., 1953), the River Klaralven (Sundborg, 1956), the Forcados River in Africa (NEDECO, 1961), the Vistula in Poland and the Volga in Russia (Jarocki, 1963), the Rio Grande (Nordin et al., 1963), the Graburn watershed in Alberta (McPherson

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[1]Use of the term sediment without additional modifiers is used to describe both the sediment concentration and sediment load.

and Rannie, 1969), the Washita River (Allen and Welch, 1967), the Colville River in Alaska (Arnborg et al., 1967), and other rivers.

The occurrence of the sediment peak after the flood peak is often attributed to its slower rate of travel which, according to Heidel (1956), conforms with a relationship observed by Seddon (1900) that flood peak travels at a greater rate that the mean water velocity, which in turn controls the wash load. However, it is also possible that spatial and temporal variations of precipitation in a basin may induce such spatial and temporal variations in sediment yield. Examples where suspended sediment followed the water discharge include the River Tigris in Iraq (Lewis, 1921), the Mississippi at Mayersville (WES, 1939), the Bighorn River in Wyoming (Heidel, 1956), the lower Rio Grande (Leopold and Wolman, 1956), and a small brook in southwest England (Walling and Gregory, 1970).

Some researchers indicate that the relative movement of the floodwave or discharge peak and sediment wave or sediment peak is related to the location of the measurement station in the basin, such that the sediment wave precedes the floodwave upstream and follows it downstream, as on the Tigris (Lewis, 1921; Gregory and Walling, 1973), the Rio Grande (Leopold and Wolman, 1956) and the Bighorn (Heidel, 1956; Allen, 1974; Richards, 1982). A study conducted on the Mississippi at Mayersville near Vicksburg (WES, 1939), which describes how the sediment concentration peak lagged the discharge peak in the 1937 flood, was used to suggest that Mayersville may be sufficiently far downriver to show the progressive downstream lag in sediment (Allen, 1974).

An additional controversy concerning hysteresis in rivers is the relationship of lead or lag with basin size. Knighton (1984) suggested that hysteresis relationships were not independent of basin size, such that in small basins the sediment peak tends to precede the discharge peak but in large basins the sediment peak may lag behind the discharge peak because upstream sources continue to supply the bulk of the sediment load, possibly because the runoff takes longer to travel from the upstream part of the basin than from the downstream part of the basin. Conversely, other studies have observed that in some large rivers the sediment peaks preceded discharge peaks by several days to several months. These include the Mississippi (Everett, 1971, Wells, 1980), the Oubangui or Ubangui (Olivry et al., 1988), and the Congo in 1987 (Olivry et al., 1988).

Most studies that have examined the timing of discharge and suspended sediment are concerned with the effects of hysteresis during floods. Hysteresis effects, however, have not been associated with the magnitude or recurrence interval of floods in previous studies. Rarely are hysteresis relationships of the silt-clay and sand components with discharge examined separately, although it is expected that they would show different relationships. The bivariate plot or loop, which was used in many of these studies, neglects the importance of time, a third variable in the process. While a lead or lag would be shown by the configuration of the bivariate plot, the length of time of the lead or lag is not shown unless every point on the loop is marked.

Problem, approach and objectives

The state of knowledge regarding statistical relationships and hysteresis between discharge and suspended sediment shows the need for a substantial number of site investigations with large and long-term data bases. The Mississippi-Atchafalaya system in southern and central Louisiana (Fig. 1) is ideal for investigating and evaluating such relationships and concepts since the discharge and suspended sediment sampling data base is more comprehensive and longer in duration than for most of the world's large rivers. It is appropriate for the study of some of the fundamental controversies and questions of discharge-suspended sediment relationships in that: 1) fine, cohesive materials are dominant in the riverborne suspended sediments and thus merit special attention; 2) sediment peaks have been shown to lead and lag discharge in previous studies; and 3) it can be used to evaluate some of the existing concepts about hysteresis effects in large rivers and at the downstream end of rivers.

Approaches utilized that have not been attempted widely in determining empirical relationships, and specifically in the study area, include: 1) computing relationships of suspended sediment concentration, rather than suspended load, with discharge; 2) relating the silt-clay and sand concentration as separate components with discharge; and 3) identifying nonlinearity in these relationships. Approaches utilized that have not been attempted widely in studying the timing of discharge and suspended sediment include: 1) identifying differences in hysteresis effects with flood magnitude; and, 2) interpreting if and in what manner the silt-clay and sand components are showing different hysteresis relationships. The results and interpretations of these phenomena in the Mississippi-Atchafalaya system may provide insights that can be used in the investigation of other large river systems with less comprehensive data, and that contribute to existing concepts of sediment transport in rivers in general.

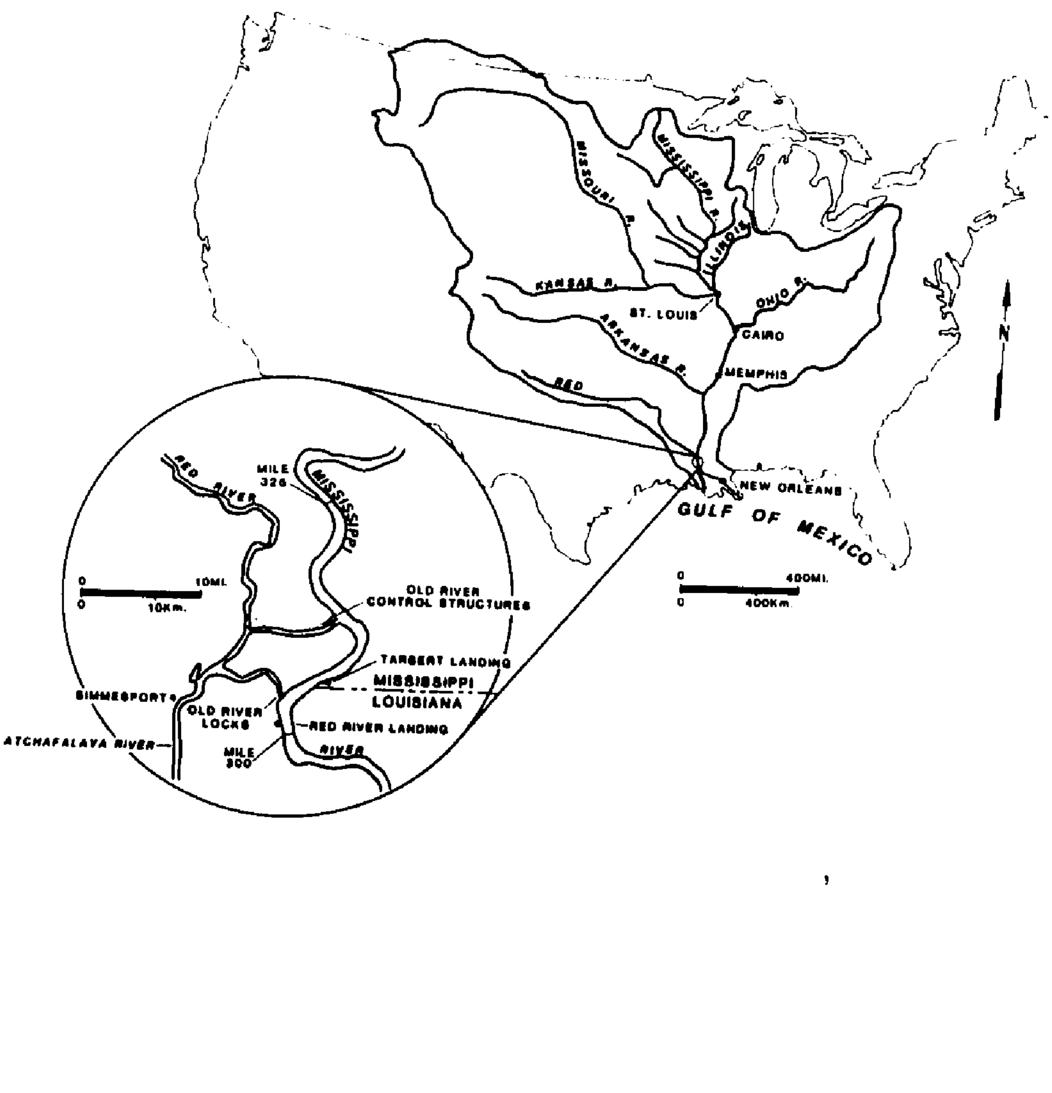


Figure 1. The drainage basin of the Mississippi-Atchafalaya river system, its major tributaries, and the system junction.

This study will identify some of the significant temporal and spatial relationships between discharge and suspended sediment in the Mississippi-Atchafalaya system in southern and central Louisiana since 1950. The primary objectives are:

1) to discuss whether the suspended silt-clay and sand follow different relationships with discharge in the Mississippi-Atchafalaya system since the silt-clay is supplied largely from the basin whereas the sand is supplied largely from the channel perimeter; and

2) to determine whether discharge-suspended sediment relationships, such as hysteresis effects, differ in high as compared to low discharge years in the Mississippi-Atchafalaya system because of physical thresholds achieved in high discharge years but not in low discharge years such as above-bankfull flow, upper flow regimes, and supply limitations.

Research findings are compared to existing studies and concepts about sediment transport in alluvial rivers, and particularly large systems. Findings are also discussed in relation to local problems in Louisiana.

Significance to local problems

Riverborne sediment is of prime importance to south Louisiana, and has been a resource for land-building through switching of delta lobes. Outside of the Atchafalaya basin, however, the effectiveness of river sediment and sedimentation has been reduced in the following ways: 1) the Mississippi River is being kept in its present course by the Old River Control Project, which causes flow to be dominant in the Mississippi rather than the Atchafalaya, funneling sediments out to the continental shelf rather than a shallow bay; 2) artificial levees along these rivers have reduced overbank sedimentation and also force most sediments to be deposited in deeper waters of the continental shelf; 3) the suspended sediment loads of the Mississippi River in Louisiana have decreased by approximately 50% since the period before 1952 due largely to human modifications in Louisiana and upstream, including revetments and dams (Keown et al., 1986; Kesel, 1988; 1989).

Unlike past conditions of net land gain in the early part of the century, Louisiana is now experiencing net land loss of about 40 square miles/year in the coastal wetlands (Gagliano et al., 1981) (Fig. 2), with reduced sediment supply certainly being one of the contributing factors to this reversal. Two of Louisiana's parishes, Plaquemines and Terrebonne, are predicted to disappear in about 50 years. If the rate of relative sea level rise continues to exceed the rate of vertical accretion on the marsh surface, disappearance of the marsh may become an even more widespread phenomena.

One proposed remediation to the coastal land loss problem on a local scale involves diversion of fresh water and sediment from the Mississippi and Atchafalaya rivers to adjacent wetlands. Two types of diversions, controlled and uncontrolled are planned. The controlled diversions entail cutting breaches through artificial levees and building flow regulation structures and retention ponds, whereas the uncontrolled diversions are simply breaches through existing levees to allow flooding and sedimentation on the wetland surface. Negative effects of controlled diversions on water supply and navigation may be minimized if sediment concentrations are maximized during flow releases, because less flow would be required to provide given quantities of sediment to the wetland environment.

Additional applications of discharge-suspended sediment relationships in the Mississippi-Atchafalaya river system include coastal planning and development, and water quality studies. Knowledge of discharge-sediment relationships can be used to enhance fish and wildlife management, shoreline change predictions, and prediction of sedimentation in coastal water bodies. Furthermore, there is an increasing awareness of the role of fine sediment in the transport of contaminants and pesticides in rivers; with additional work, this data can be used to infer potential impacts to water supplies, fisheries, and wildlife resources in the alluvial and coastal environment.

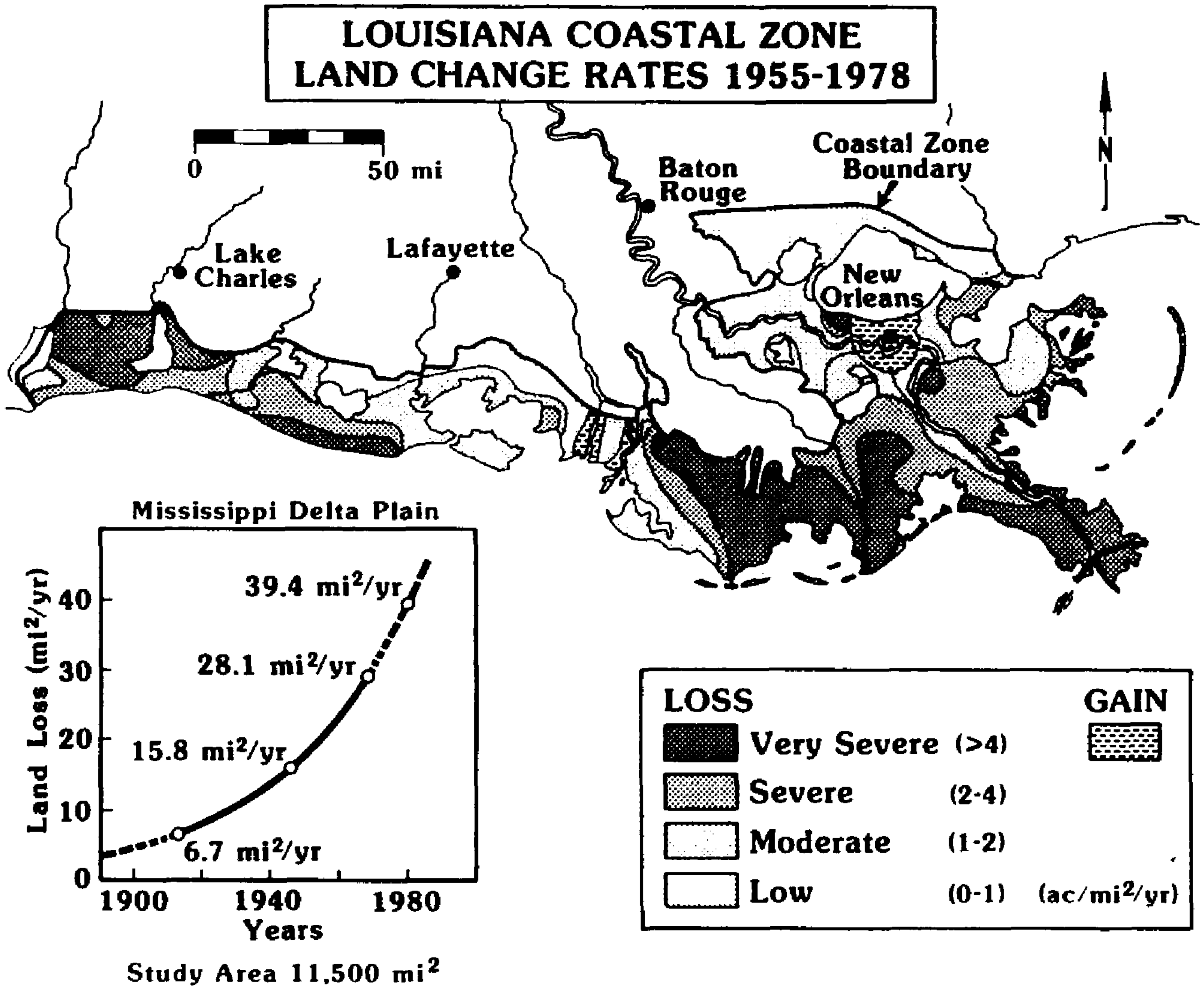


Figure 2. Land loss rates in coastal Louisiana (from Gagliano et al., 1981).

Data base

Sampling locations in the study area, periods, and data sources are shown in Figure 3 and Table 2. Daily stage data and discharge estimates and periodic suspended sediment data used in this study were collected by the U.S. Geological Survey (USGS) and the U.S. Army Corps of Engineers (COE), often in cooperation, with the agency reporting to the Office of Water Data Coordination (OWDC).[2] The data base consists of over 3000 point-integrated instantaneous measurements of discharge, suspended sediment concentration, and percent sand in the suspension collected since 1950.

Discharge measurements were acquired, in part, from COE publications entitled "Stages and Discharges of the Mississippi River and Tributaries and Other Watersheds in the New Orleans District". Since 1972, some of the discharge and sediment data have been published in Water Resources Data (WRD) publications (USGS, 1972-88). The majority of these data, however, were acquired as unpublished and, in some instances, raw data at the Hydrologic and Hydraulics Division of the New Orleans (NOD) and Vicksburg (VXD) districts, the Potamology Section of the Lower Mississippi Valley Division, Mississippi River Commission (MRC).

[2]The data collected by these agencies are published in English units. The results are similarly reported in English units such that they can be compared with previous studies, although in some cases both English and metric units are given. A conversion table for these units is given following the List of Tables in the preface.

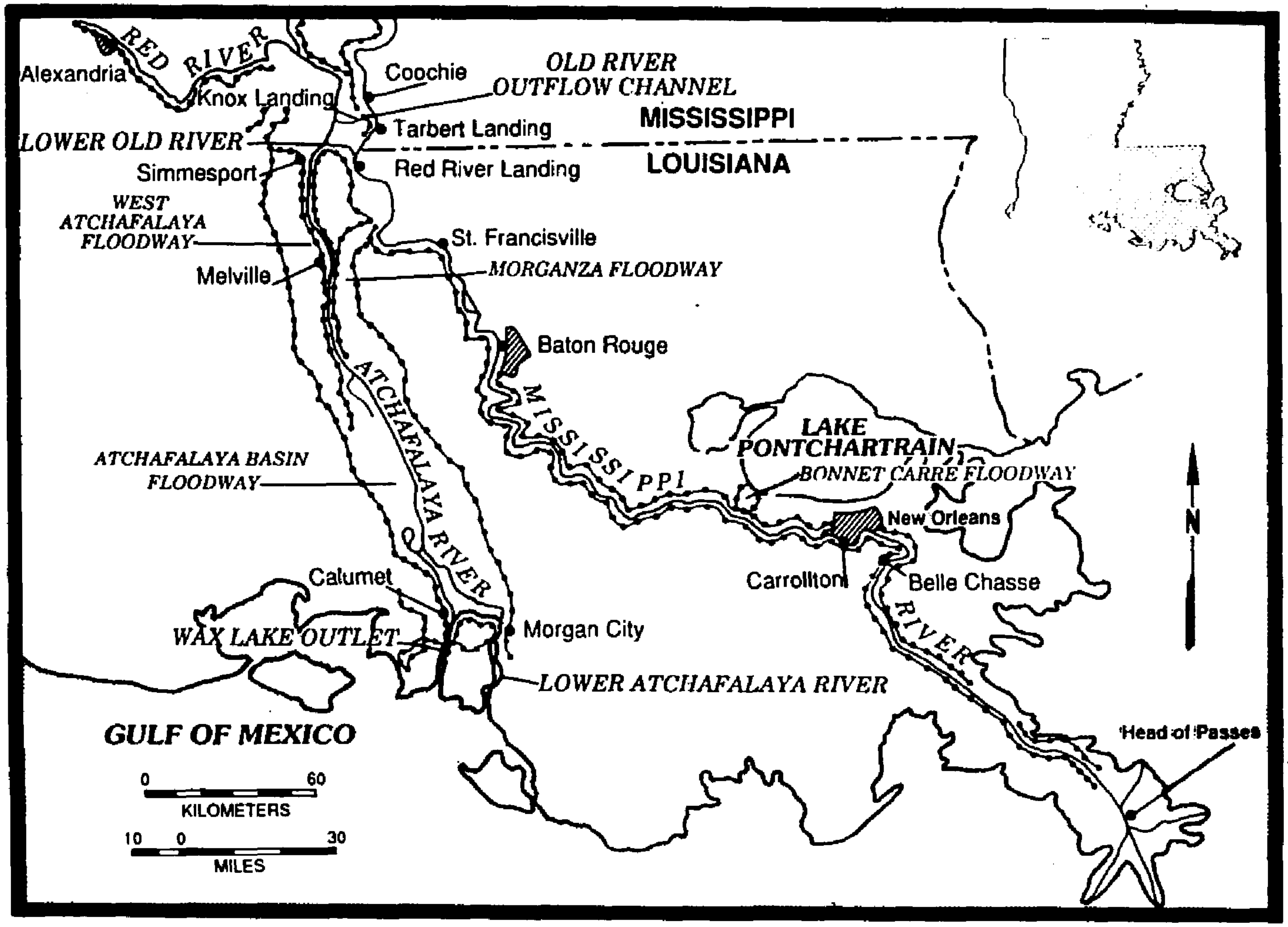


Figure 3. Location of suspended sediment data stations, floodways, and levees in the study area.

Table 2. Sampling locations, period of record, and number of composite point-integrated suspended sediment measurements used in this study.

LOCATION	PERIOD	N	SOURCE
Mississippi River			
Baton Rouge (mile 233.8)	1950-58	182	NOD, unpub.
Red River Landing (mile 301.3)	1958-63	121	NOD, unpub.
Tarbert Landing (mile 306.3)	1963-87	819	NOD, unpub. & USGS
Belle Chasse (mile 76.0)	1977-88	103	USGS, WRD
Atchafalaya River System			
Simmesport (Atchafalaya, mile 4.9)	1950-63	297	MRC, unpub.
Simmesport (Atchafalaya, mile 4.9)	1963-87	729	NOD, unpub. and USGS
Alexandria (Red River, mile 104.9)	1963-87	511	NOD and VXD, unpub
Knox Landing (Old River OC, mile 5.5)	1963-87	617	NOD, unpub.

REGIONAL SETTING AND PHYSICAL CHARACTERISTICS

General characteristics of the study area

The study area is located south of latitude 31°20'N in south and central Louisiana, extends to the Gulf of Mexico, and includes the Mississippi, Red, Old, and Atchafalaya rivers (Fig. 3). The generalized geology of the study area, which includes the Mississippi and Red river alluvial valleys to the north and the Mississippi River delta plain to the south is shown in Figure 4. Some characteristics of the drainage basins or river systems in the study area are listed in Table 3. The Mississippi River and the Red River are of primary interest, in that they supply the Old and Atchafalaya rivers with flow and sediment. Although earlier this century the Old River system was bidirectional, flow is now toward the Atchafalaya and is controlled at about 30% of the Mississippi flow upstream of it. The Atchafalaya River system is formed at the confluence of the Red River and the Old River system, receiving flow from both.

Flow and channel characteristics

Extreme discharges and stages in the study area may be associated with excess runoff, snowmelt, high antecedent moisture, storm surges, diversions from other basins, and combinations of these factors. Discharge from the Mississippi basin is markedly seasonal, with low flow occurring in the summer and fall, and high flow during the winter and spring (Jordan, 1965; Roberts et al., 1980); precipitation is generally abundant throughout the year and flow is sustained during dry periods by groundwater discharge. In the Red River basin, precipitation is not as abundant and floods are more episodic, with shorter, more peaked events. Stage variations in the Mississippi (Fig. 5), Atchafalaya, and Red rivers generally decrease downstream because of the lower gradients. The effects of tides increase downstream in the Mississippi and Atchafalaya rivers and may be discernible as far upstream as Lower Old River during extreme low water (Ferguson, 1940; Kolb, 1962). Stage maxima, means, and minima for the Mississippi-Atchafalaya river system are given in Table 4.

Table 3. Drainage basin and channel characteristics, Mississippi-Atchafalaya river system, southern and central Louisiana.

AREA	LENGTH (Old River to Gulf)	BASIN CLIMATE	HYDROLOGY	BASIN GEOLOGY
Mississippi River				
1,124,000 mi^2	325 mi	Humid to semiarid	Seasonal	Complex
Red River				
93,244 mi^2	N.A.	Semiarid	Episodic	Permian red beds
Old River System				
Indeterminate	N.A.	N.A.	Controlled @ 30% of Mississippi River above diversion	N.A.
Atchafalaya River				
Indeterminate	125 mi	N.A.	Combined flow Red and Old rivers	N.A.

As one progresses downstream in both the Mississippi and Atchafalaya rivers, the banks are composed of progressively finer deposits. In the Mississippi, meanders decrease in number; and the channel becomes narrower, straighter, and deeper. Sandbars are rare and no major tributaries enter the study area; the last mid-channel island in the Mississippi River lies just above Donaldsonville and according to Fisk (1944) represents the approximate southern limit of low-water sand transfer by the river. The Plaquemines-Modern delta, though deteriorating in most sections, is prograding in others. A summary of several physical characteristics of the Mississippi River as described in previous studies is shown in Figure 5, with river miles computed as AHP or Above the Head of Passes.

The Atchafalaya River is relatively straight and has few meander loops, in contrast with most other streams in the Mississippi River alluvial valley. In the northern part of the basin, flow is confined principally to a single channel; in the southern part, flow is divided between numerous interconnected channels, bayous, and lakes. Several lakes in the basin have experienced gradual infilling over time (Latimer and Schweizer, 1951; Fisk, 1952; Tye and Kosters, 1986). The basin has

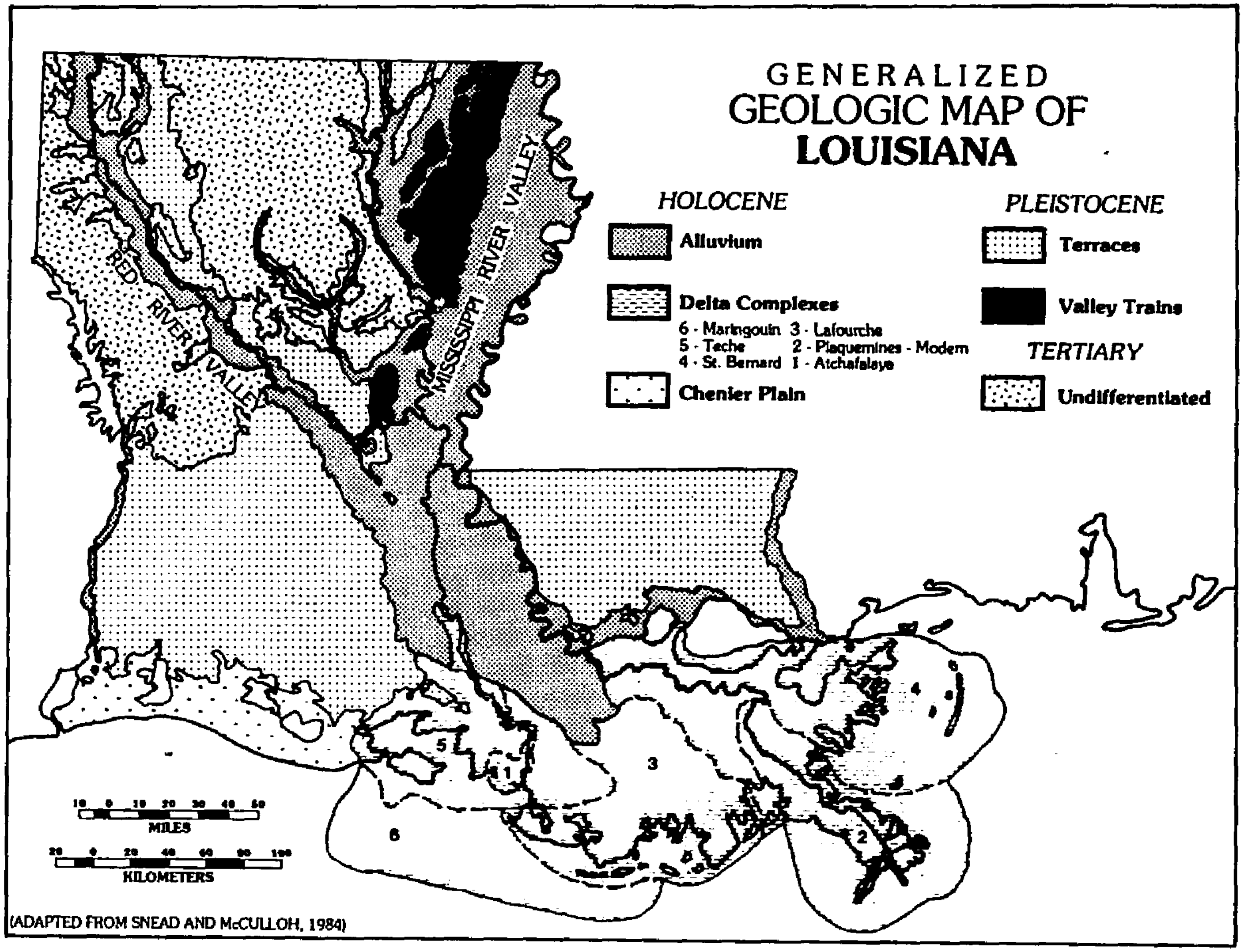


Figure 4. Generalized geology of Louisiana (adapted from Snead and McCulloh, 1984).

Table 4. Stage observations in feet in the Mississippi-Atchafalaya river system in southern and central Louisiana, converted to mean sea level (from New Orleans District, 1974 and 1985; U.S. Geological Survey, 1989).

STAGE (in ft m.s.l)			
Maximum	Minimum	Bankfull	Low Water
<u>Mississippi River</u>			
Tarbert Landing			
61.20 (1973)	8.2 (1956)	51	12.3
Red River Landing			
60.94 (1927)	2.89 (1895)	46	10.6
Baton Rouge			
49.28 (1927)	-0.07 (1894)	29	2.6
New Orleans-Carrollton			
21.27 (1922)	-1.60 (1872)	11	0.5
<u>Red River</u>			
Alexandria			
89.46 (1945)	40.56 (1881)	78.26	45.06
<u>Old River and Outflow Channel</u>			
Knox Landing			
59.30 (1973)	1.32 (1964)	49	8.0
Torras Landing			
61.6 (1927)	3.3 (1939)	------	------
<u>Atchafalaya and Lower Atchafalaya River</u>			
Simmesport			
59.13 (1927)	0.70 (1976)	46	6.9
Morgan City			
10.53 (1973)	-5.44 (1976)	4	-0.8

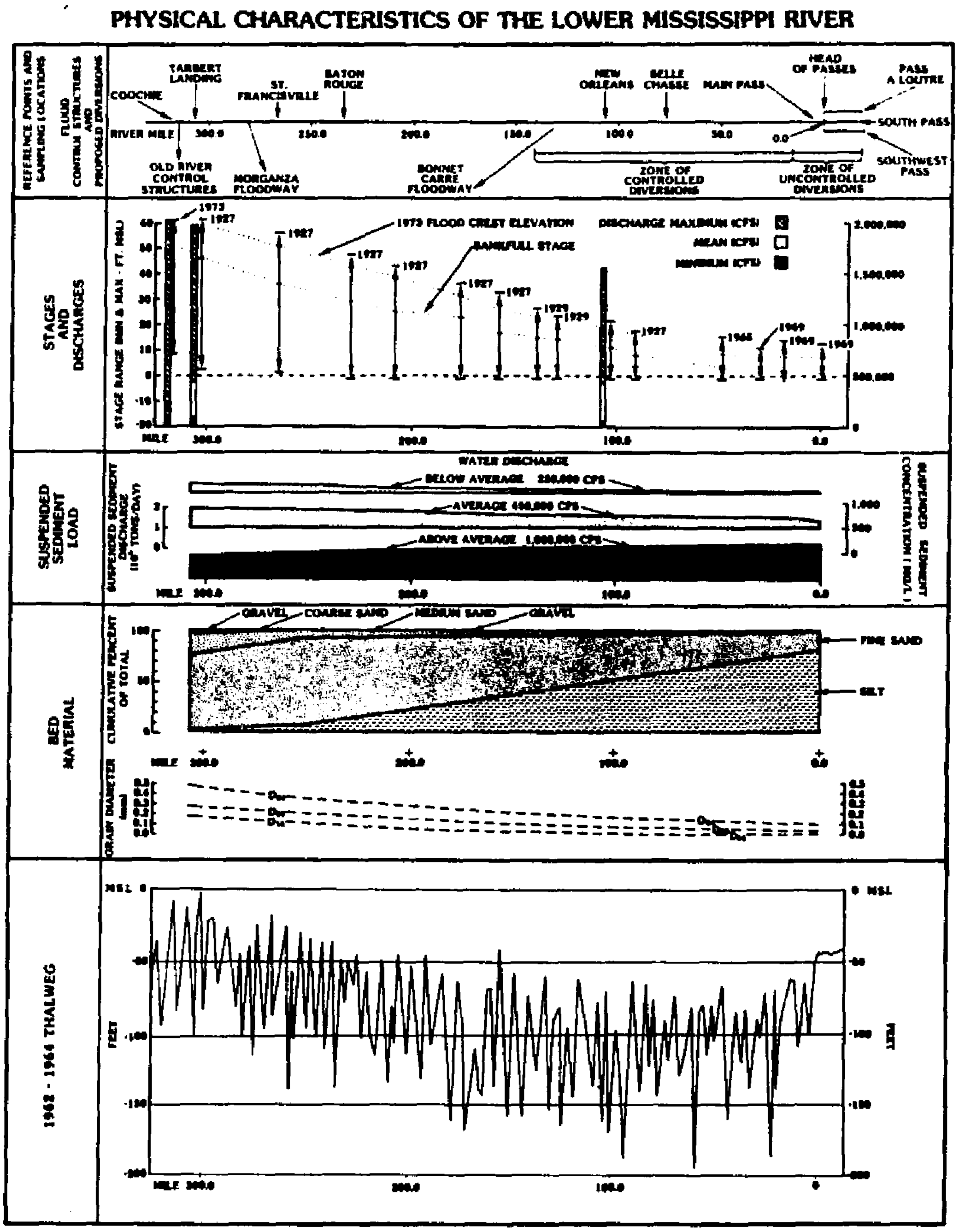


Figure 5. Physical characteristics of the Lower Mississippi River in the study area. Sources include Keown et al. (1977) and New Orleans District (1984a, b) for miles and structures; New Orleans District (1985) for stages and discharges with years of peak stages indicated; Everett (1971), Wells (1980), and Meade (1987) for suspended sediment; Keown et al (1986) for bed material; and Mississippi River Commission (1971) for thalweg elevations.

two outlets to the Gulf, the Lower Atchafalaya River and the Wax Lake Outlet, which have deltas that initiated a subaqueous phase in the early 1950s and have developed subaerial expression since the early 1970s (Cratsley, 1975; Shlemon, 1975; Rouse et al., 1978; Roberts et al., 1980).

The size of the bed material, which can vary appreciably within a given cross section in the Mississippi and Atchafalaya rivers (Wells, 1980; Watson, 1982), shows pronounced downriver trends (Keown, 1981, 1986) (Figure 5). Bed material decreases downriver in the Mississippi from about 96% fine and medium sand and 1% silt near Old River, to about 30% fine sand and 70% silt and clay near Belle Chasse, to about 20% fine sand and 80% silt and clay at the Head of Passes (Keown, 1981; 1986) (Fig. 5). Similarly, upstream on the Atchafalaya at Simmesport, bed material is composed mainly of fine sand (Keown et al., 1977). Further downstream, fine material predominates and coarse material occurs in smaller quantities.

The Red River and Old river system, the sources for the Atchafalaya, differ greatly in their hydrology and characteristics. The Red River is a shallow, unstable meandering stream for much of its length, characterized by wide variations in depth, shifting channels, and caving banks (Waterways Experiment Station, 1950). Lower Old River, the former connection with the Atchafalaya, was receiving increasing flow from the Mississippi before it was artificially closed on July 12, 1963, when it was converted to a navigational lock and dam system. The controlled system which replaced it diverts flow through the Old River Outflow Channel and includes the Old River Low Sill and Overbank structures and the Old River Auxiliary Structure (Table 5). Several individuals believe that despite these structures, diversion to the Atchafalaya is imminent because of its shorter route to the Gulf of Mexico. The Atchafalaya "..lies there like a big alligator in a low slough, with time on its side, waiting-waiting to outwait the Corps of Engineers-and hunkering ever down lower in its bed and presenting a sort of maw to the Mississippi, into which the river could fall" (McPhee, 1989).

Existing and proposed modifications in and upstream of the study area

A number of natural and human-induced changes in and upstream of the study area affect the flow and sediment regime of the study area (Fig. 3 and 6; Table 5). The system of floodways and diversions on the Mississippi-Atchafalaya system (Fig. 3; Table 5) has greatly modified the flow regime (Lower Mississippi Valley Division, 1987; Chin et al., 1975). Other important modifications include land use changes, dams and reservoirs, artificial levees, cutoffs, and revetments. Forest and vegetated land had given way to cleared land between 1860 and 1930 (Keown et al., 1981), resulting in accelerated rates of runoff, snowmelt, soil erosion, and bank caving. Moreover, flood control dams and reservoirs, particularly on the Missouri and Arkansas, have caused both reduced concentrations and moderation of seasonal discharge extremes on the Mississippi (Keown et al., 1981; Kesel, 1988a and b). Progressive heightening, lengthening, and widening of artificial levees since the 18th century initially reduced and have since eliminated overbank flooding and crevassing (Elliott, 1932; Latimer and Schweizer, 1951; New Orleans District, 1970). Cutoffs for navigation improvements, particularly those made between 1929 and 1942 on the Mississippi River upstream of the study area between Memphis and Angola have caused a number of channel adjustments, particularly changes in stage-discharge relationships (Elliott, 1932; Ferguson, 1940; Warren, 1974; Winkley, 1977; New Orleans District, 1958). Revetments, common in and upstream of the study area (New Orleans District, 1970, 1977, 1988), prevent the recession of caving banks to the artificial levees, maintain the shorter post cut-off alignment of the river, and have caused a corresponding decline in sediment volume in the Lower Mississippi River (Winkley, 1977).

Channel modifications recently completed or in construction include: a series of five locks and dams, accompanied by cutoffs and revetments, to make the Red River navigable upstream to Shreveport (Vicksburg District, 1987); the Mississippi River Saltwater Barrier (mile 63) completed in the drought of 1988 to reduce the frequency and duration of saltwater intrusion events (Soileau et al., 1989); and freshwater and sediment diversions, recently proposed with construction in progress, to reduce salinity and land loss in wetlands adjacent to the Mississippi River (New Orleans District,

Table 5. Some major structures and floodways, Mississippi-Atchafalaya river system, southern and central Louisiana (data from Lower Mississippi Valley Division, 1987).

STRUCTURE (date of completion)	FUNCTION AND HISTORY OF USE
Structures	
Old River Low-Sill Control (1959)	Diversion to Atchafalaya of approximately 30% of the flow of the Mississippi River above Old River Control daily
Old River Overbank Control (1959)	Diversion to Atchafalaya from Mississippi during floods of 1973, '74, '75, '79, '83, '84, & '85
Old River Lock and Dam (1963)	Closure of Lower Old River to control diversion yet continue use for navigation
Old River Auxiliary (1987)	Diversion to Atchafalaya in combination with Low-Sill Structure
Wax Lake Outlet (1942)	Diversion to Gulf of approximately 30% of the flow of the Lower Atchafalaya daily
Floodways	
Bonnet Carre Floodway (1936)	Diversion to Lake Pontchartrain during floods of 1937, '45, '50, '73, '75, '79, & '83 from Mississippi
Morganza Floodway (1954)	Diversion to Atchafalaya from Mississippi during 1973 flood
West Atchafalaya Floodway (N.D.)	Diversion from upper Atchafalaya to Lower Atchafalaya; not used to date

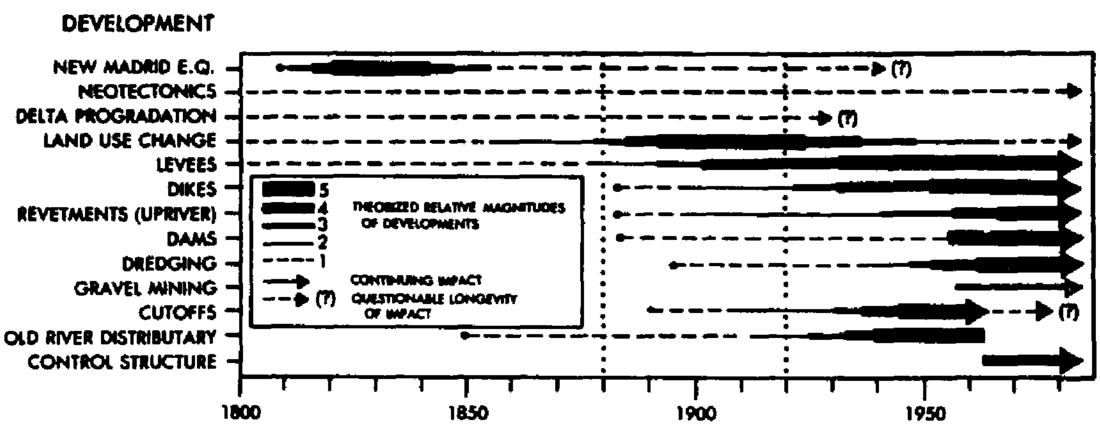


Figure 6. The theorized magnitude of natural and human-induced changes on the sediment regime of the Mississippi-Atchafalaya river system (from Davison, 1985 and Kesel, 1988). Channel modifications recently completed or in construction may supplement these effects.

1984; Lower Mississippi Valley Division, 1987). These projects, particularly the revetments on the Red River, will reduce sediment loads in the Mississippi-Atchafalaya system in the future.

Empirical relationships of instantaneous measurements

The results of empirical studies on the Mississippi and Atchafalaya, as elsewhere throughout the world, show that comparison of suspended load with discharge, rather than concentration with discharge, is not particularly revealing (Fig. 7a and b). Jordan (1965) examined water years 1949 to 1958 annually for the Mississippi River at St. Louis, computed the exponents of the power law discharge-suspended load relationships, but did not provide corresponding correlation coefficients or confidence intervals for these relationships. No consistent relations were found when particle size parameters were plotted against discharge, season, temperature, or concentration as independent variables. The relationship between suspended load and discharge was determined for 42 instantaneous measurements collected on the Mississippi River at Tarbert Landing at some time between 1958 and 1973 by Sedimentation Seminar (1977). The exponent describing the function, the correlation coefficient, and confidence interval were not given. Wu (1985) grouped sediment load data on the Atchafalaya River at Simmesport into seasons, and computed exponents, coefficients, and correlations for each season. He found that regressions of load with discharge showed greatest slopes in summer and the lowest slopes in spring, and that correlation coefficients for all seasons were between 0.89 and 0.92. All three studies, as is common elsewhere (Walling, 1974), found a linear log-log relationship between the variables because sediment load is computed from discharge.

Robbins (1977) examined suspended sediment data from the Mississippi River at Arkansas City (mile 566), Vicksburg (mile 436), and Natchez (mile 362) between water years 1966 and 1974 and contrasted them with data from 1929-1931 studies (Fig. 7c and d). Discharge was plotted against suspended sediment load, suspended silt-clay load, suspended sediment concentration, and suspended sand concentration for each water year. Plots of the total suspended sediment concentration and discharge for the 1973 water year at all three locations and the 1974 water year at Natchez did not follow a simple linear log-log function and were instead nonlinear. The suspended sediment for a given discharge was generally greater for rising stages than for falling stages in 1973. Robbins suggested that the decrease in concentration occurred when the stage went bankfull, and therefore it was probably related to decrease in velocity and hydraulic efficiency. However, the nonlinearity was most pronounced in the material finer than sand, which generally is not directly related to the velocity. Exponents were computed for linear but not the nonlinear functions, and corresponding correlation coefficients and confidence intervals for either linear log-log or nonlinear log-log relationships were not provided. It is therefore unknown how well these relationships explain the variance, nor whether the relationships for various water years were statistically different. The graphs of the nonlinear relationships appear quadratic, although it was not stated which type of relationship would be most appropriate.

The occurrence of nonlinear relationships of concentration with discharge is intriguing in several respects. First, it indicates that the relationships between suspended sediment concentration and discharge in the system may be nonlinear, but that the regressions of load and discharge have masked such relationships. Secondly, results indicate possible differences in behavior between high and low discharge years, because nonlinearity was apparent during a very high discharge year in 1973 at all three locations, and during another high discharge year in 1974 at Natchez. Furthermore, the decrease in concentration at high discharges being most pronounced in material finer than sand indicates that the silt-clay and sand components indeed might behave distinctively and that they should be assessed separately.

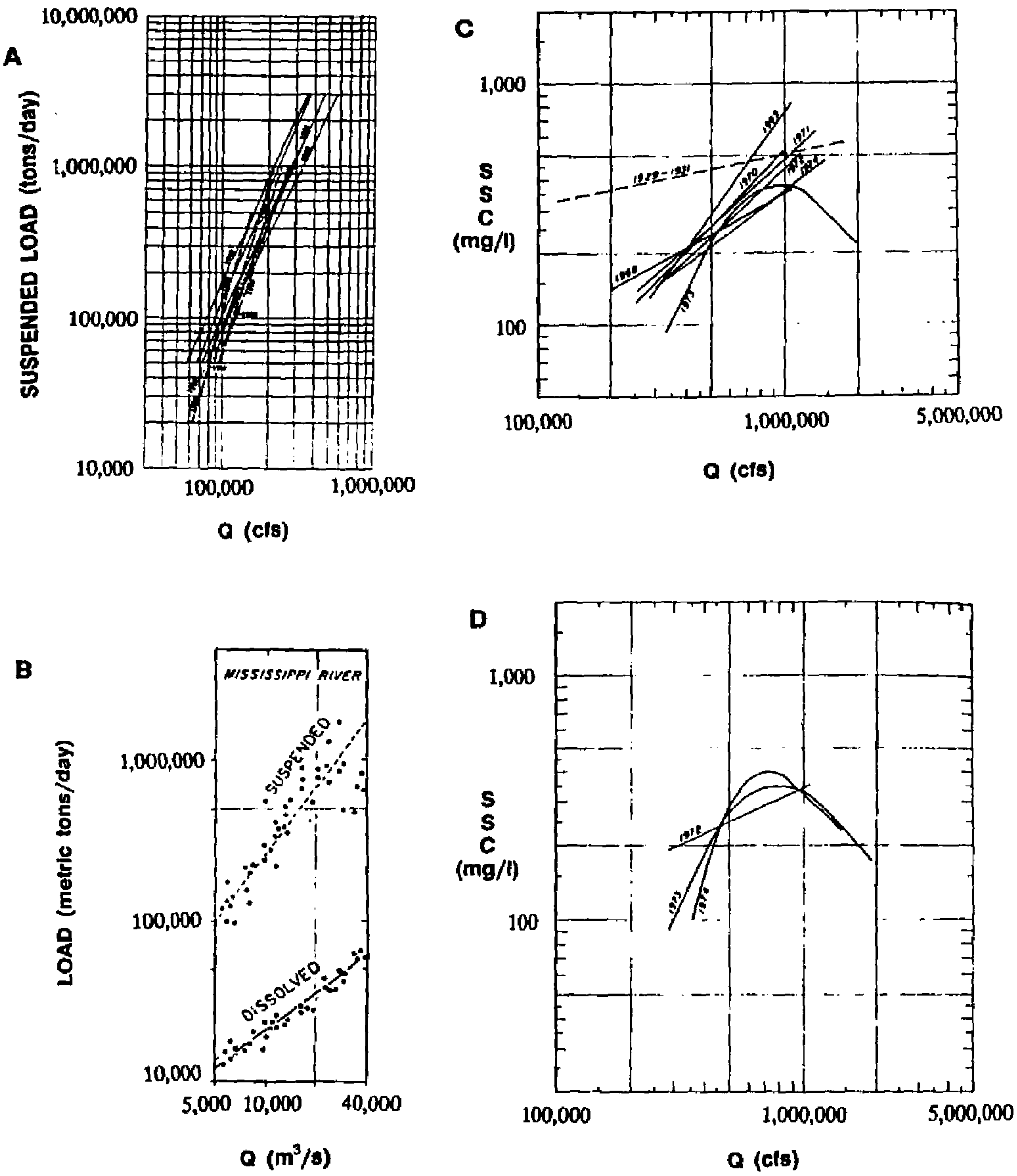


Figure 7. Results of previous studies of statistical relationships in the Mississippi River: a) from Jordan, 1965 at St. Louis; b) from Sedimentation Seminar, 1977 at Baton Rouge and Tarbert Lg.; c) from Robbins, 1977 at Vicksburg; d) from Robbins, 1977 at Natchez.

Hysteresis effects

Nonlinearity in discharge-suspended sediment relationships, as shown in Figures 7c and d such that high concentrations are manifest at intermediate discharges and low concentrations are manifest at high discharges, indicates that discharge and suspended sediment are not at a maxima concurrently. Should discharge-suspended sediment relationships in the study area show a similar shape as 1973 and 1974 in Figure 7c and d, where highest concentrations occur at intermediate discharges, it follows empirically, that if this relationship were without scatter, that during a single crest event in a high discharge year, two peaks would occur. One sediment peak would lead the discharge peak on the rising limb and the other would lag the discharge peak on the falling limb.

In many instances, however, the suspended sediment concentration on the rising limb is not the same for a given discharge as on the falling limb and shows hysteresis effects, which is one explanation for the large scatter typically found on discharge-suspended sediment graphs. If, as Robbins (1977) described for the three locations, the suspended sediment for a given discharge is generally greater for rising stages than for falling stages, suspended sediment would lead the discharge temporally. If, as described for Mayersville (WES, 1939; Allen, 1974), suspended sediment lags the discharge temporally, then other types of hysteresis effects may be apparent. High discharge years, which show the greatest nonlinearity in Robbins' (1977) plots, should show the greatest lead and lag, or hysteresis effects.

Other studies have illustrated hysteresis effects on the Mississippi, and found that peak sediment concentration generally occurs before peak discharge during flood events. Bivariate plots of suspended sediment load or concentration against discharge were graphed for the Mississippi at Red River-Tarbert landings in January-March 1960, January 1964, and March-April 1964 by Everett (1971), and for November 1972, November-December 1974, and January 1975 by Wells (1980). Hysteresis was ascribed to the supply or availability of sediment being less than the river was capable of transporting at high discharges.

While it is noteworthy that hysteresis has been observed during several events, more remains to be understood regarding the relative timing between discharge and suspended sediment peaks on the Mississippi-Atchafalaya river system. For example, the length of time between peaks, the occurrence of peaks other than those preceding floods, the relationships of hysteresis with flood magnitude, and the differences in hysteresis relationships between the sand and silt-clay components have not been examined at all. Understanding of the system may be improved if time were examined in greater detail than allowed by bivariate plots, if temporal variations were examined for periods longer than three months, if the magnitude of flood events were examined in detail, and if temporal changes in silt-clay or sand composition were noted in some manner.

METHODS

Field sampling strategy

Field procedures by the COE and USGS for suspended sediment sampling in the Mississippi-Atchafalaya river system followed the point-integration method because of the large river depths (Federal Inter-Agency Sedimentation Project, 1963; Guy and Norman, 1970). Fifteen to forty points were acquired per cross section (Keown et al., 1977) to adequately sample the vertical and lateral variations in concentration of the sand fraction. The sediment samplers are designed to minimize turbulence caused by the sampler shape, to permit correct orientation into the flow, and to maintain similar velocities at the sampler intake as in the stream cross section (Guy and Norman, 1970). Instantaneous measurements of discharge, suspended sediment concentrations, and percentage sand in suspension were collected twice-weekly to twice-monthly, and sometimes more frequently at high discharges.

Assessment of discharge and suspended sediment means, extremes, and trends

Annual summary data were used to examine historic variations in the Mississippi-Atchafalaya river system. The annual values were summarized by the COE and USGS by estimating the trend between instantaneous measurements by using annual power rating curves and linear interpolation methods (Porterfield, 1972; New Orleans District, unpublished data). The suspended sediment sampling locations for the Mississippi, which were moved from Baton Rouge to Red River Landing to Tarbert Landing by the COE, were combined into one station named Mississippi River below diversion (MRBD).

Flood frequency analysis and nonparametric tests for independence, trend and randomness were performed using the Consolidated Frequency Analysis Package (Pilon et al., 1985) for the period between 1950 and 1985 for annual maxima on the Mississippi and Red rivers, since these provide flow to the other locations. Nonparametric statistical tests for independence, trend, and randomness were conducted for the mean discharges, mean sediment loads, and mean concentrations for all four rivers. Two events were considered independent only if the probability of occurrence of either was unaffected by the occurrence of the other. Trend tests were used to determine whether there was a trend in the magnitude of the data when arranged in chronological order. If the trend was significant, a linear regression was performed to assess the direction and magnitude of the trend. The presence of dependence or trend and its significance were determined with the Spearman rank order correlation coefficient. The nonparametric test for general randomness was based on the runs above and below the median (Pilon et al., 1985).

In the flood frequency analysis, the annual series data for the period between 1950 and 1985 were ordered, ranked, and fit with various distributions. Four distributions, the Generalized Extreme Value (GEV), the Three-Parameter Lognormal (3PLN), the Log Pearson Type III (LPT3), and the Wakeby (WKBY), were used in the flood frequency analysis. The Wakeby distribution is the only five-parameter distribution, whereas the other distributions are based on three parameters; it is thus the most flexible and can assume shapes such as "S-bends" and "hockey-sticks", unrealizable by the other more conventional distributions (Pilon et al., 1985). However, it is considered to be valid only if specific parameter combinations are met (Pilon et al., 1985). For all the distributions, the theoretical coefficients of skewness and kurtosis, by virtue of the logarithmic transformation, should be 0.0 and 3.0, respectively. These theoretical characteristics can be used to make a subjective assessment of how well the distribution fits the data sample of annual floods. Details of the distributions and additional references for consultation are described in Pilon et al. (1985).

Assessment of empirical discharge-suspended sediment relationships

Data were input and transformed such that log-log relationships could be applied to discharge and various suspended sediment parameters (Table 6). Outliers were generally included in the analysis although it is unknown whether they represent true values or measurement and other types of errors. Occasional missing instantaneous discharges on the Mississippi and Atchafalaya rivers were replaced with mean daily discharge values at Tarbert Landing and Simmesport. Concentrations and percent sand in suspension were computed from point-integrated measurements where necessary. Preliminary plots indicated that it was appropriate to compute LOGQ2 or the square of LOGQ for application in quadratic log-log relationships.

Regression statistics and plots were produced with the LOGSSED, LOGSSEDQ, LOGSDCO, LOGSTCL, and PCTSAND as dependent variables, with ten regression tables for each location. For the linear log-log regression, the LOGQ was the independent variable. For the quadratic log-log regression, LOGQ and LOGQ2 were the independent variables. The quadratic and linear log-log statistical models were compared using a test of the full and reduced regression (Neter et al., 1983). This test was attempted to determine whether the additional parameters in the quadratic model substantially reduce the variance of the observations around the fitted regression line. The test statistic, F*, is a function of the error sum of squares of the reduced model SSE(R), and the error sum of squares of the full model SSE(F), namely:

$$F^* = [(SSE(R) - SSE(F)) / (df_R - df_F)] / [SSE(F)/df_F]$$

where df_R and df_F are the degrees of freedom for the reduced and full models.

Table 6. Input variables and transformations for statistical analysis.

INPUT VARIABLES	TRANSFORMATIONS [EXCEPTIONS]
QCFS (cfs)	SUSSEDQ (tons/day)= 0.0027 * QCFS * SUSSED
SUSSED (mg/l)	SANDCON (mg/l)= SUSSED * (PCTSAND/100)
PCTSAND (%)	STCLCON (mg/l)= SUSSED * (100-PCTSAND/100)
DATE (mmddyy)	LOGQ = LOG(QCFS)
	LOGSSED = LOG(SUSSED)
	LOGSSEDQ = LOG(SUSSEDQ)
	LOGSDCO = LOG(SANDCON) [Missing if PCTSAND = 0 or Missing]
	LOGSTCL = LOG(STCLCON) [Missing if PCTSAND = Missing]
	LOGQ2 = LOG(QCFS)**2

<u>Assessment of hysteresis and other temporal variations</u>

Time series plots of discharge, suspended sediment concentration, suspended sediment load, and percent sand in suspension were produced for several locations. Daily suspended sediment estimates were available for Baton Rouge (WY 1950-57), Red River Landing (WY 1958-63), Tarbert Landing (WY 1964-85), Simmesport (WY 1964-85), Alexandria (WY 1964-80), and Knox Landing (WY 1963-85). Simmesport (WY 1950-62) also had relatively frequent sampling, but not interpolations. Instantaneous measurements are represented where percentage sand in suspension is shown, which enables comparison of actual observations with the estimated or predicted values between sampling dates. Most, though not all of the instantaneous measurements are shown because percent sand values were sometimes not determined during the early 1950s and more recently on occasion.

Units for discharge (Q) on the graphs for the Mississippi, Atchafalaya, and Old rivers are in millions of cfs, suspended sediment concentrations (SSC) in thousands of mg/l, suspended sediment loads (SSQ) in millions of tons/day, and percent sand is listed directly. Units on the Red River are similar, except for discharges where 1 unit equals 100,000 cfs. Graphs for each location were scaled similarly throughout the period of record. Days from the beginning of the water year, October 1, are shown on the x-axis. A conversion chart is provided to compare the beginning date of each month to days in the water year sequence (Table 7).

Representative years were chosen to identify if hysteresis effects and other temporal discharge-suspended sediment relationships show differences from high to low discharge years. All years with maximum discharges with a return period greater than 20 years and less than 1.05 years were examined, along with years with maximum discharges closest to the major return periods chosen in the flood frequency analysis program, e.g., 5, 2, and 1.25 years. These intervals constitute a fairly evenly spaced distribution on a probability scale.

Table 7. Conversion of day number of water year to month and day of calendar year.

NON-LEAP YEAR Date	Water year day	LEAP YEAR Date	Water year day
October 1	Day 1	October 1	Day 1
November 1	Day 32	November 1	Day 32
December 1	Day 62	December 1	Day 62
January 1	Day 93	January 1	Day 93
February 1	Day 124	February 1	Day 124
March 1	Day 152	March 1	Day 153
April 1	Day 183	April 1	Day 184
May 1	Day 213	May 1	Day 214
June 1	Day 244	June 1	Day 245
July 1	Day 274	July 1	Day 275
August 1	Day 305	August 1	Day 306
September 1	Day 336	September 1	Day 337

DISCHARGE AND SUSPENDED SEDIMENT: MEANS, EXTREMES, AND TRENDS

Background work regarding variations in discharge and suspended sediment magnitude is important to characterize the spatial and temporal differences in the system, the typical range of behavior, and to identify nonstationarity or trends in the data. It is also necessary to pinpoint years which should be examined in detail because of unusual phenomena, such as extreme floods, low flows, and perturbations in the discharge and sediment regime.

Discharge means, extremes and trends

Flow in the Mississippi River below the diversion is fairly consistent, and fluctuates only two- to three-fold from extremes of maxima, means, and minima (Fig. 8). The regularity of flow is related to the large basin size, the humid climate with precipitation throughout the year, and its ability to store groundwater. Years with high annual mean discharges typically coincide with high annual maximum discharges. For the period between 1950 and 1985, maximum discharges do not display significant serial dependence or trend, and are significantly random at the 5% significance level (Table 8). Mean discharges for the same period do not show significant trend. However, they show highly significant serial dependence at the 1% significance level, which indicates that discharges are influenced by antecedent conditions. Mean discharges are also not significantly random at the 5% significance level, indicating long-term cyclic patterns.

For the Mississippi below the diversion, the flood frequency regimes computed using the Generalized Extreme Value, the Three-Parameter Log-Normal, and the Log Pearson Type III distributions are similar (Table 9). The Wakeby distribution shows floods of the same magnitude for return periods of 5 to 500 years and is considered to be invalid. Of the three valid distributions, none is considered superior based on the coefficients of skewness and kurtosis. The four largest flood events, 1973, 1983, 1950, and 1979, have return periods between 20 and 50 years for all three distributions; the largest of these in 1973 is closer to the discharge associated with the 50 year return period, whereas the smallest of these in 1979 is closer to the discharge associated with the 20 year return period (Tables 9 and 10). The remainder of the events have return periods of less than 10 years. Exactly half of the events have a return period of 2 years or less.

The Red River at Alexandria shows highly variable maximum, mean, and minimum discharges from year-to-year, and fluctuates about seven-fold over the period of investigation, proportionately more so than the Mississippi (Fig. 8). The precipitation in the Red River basin is not as regular or abundant as the Mississippi, therefore it does not have the sustained baseflow and floods are more episodic. Unlike the Mississippi, the years with high mean discharges are not often the same as years with high maximum discharges. In some years, with numerous events, mean flows may be high although no single event stands out. Conversely, a single large event may dwarf the remainder of annual hydrograph and the resultant mean annual flow would not be large. At the 5% significance level for the period of record for this investigation, the maximum and mean discharges do not display serial dependence or trend, and the data are random (Table 8).

For the Red River at Alexandria, the flood frequency regimes computed using the four distributions are fairly close, particularly for events with return periods between 1.25 and 20 years (Table 9). The Wakeby distribution shows floods of dissimilar magnitude compared to the other distributions for short return periods ($\leq$ 1.050 years) and for long return periods ($\geq$ 50 years), but few events show such short or long return periods. Of the four distributions, no one distribution is considered superior based on the coefficients of skewness and kurtosis. The three largest events, 1958, 1957, and 1953, have return periods between 20 and 50 years with all four distributions, however, corresponding sediment data are not available until 1963 (Tables 9 and 10). The next three largest events, 1966, 1968, and 1950, have return periods between 5 and 10 years. None of these years, except for 1950, correspond to years with high discharges or return periods greater than 5 years on the Mississippi.

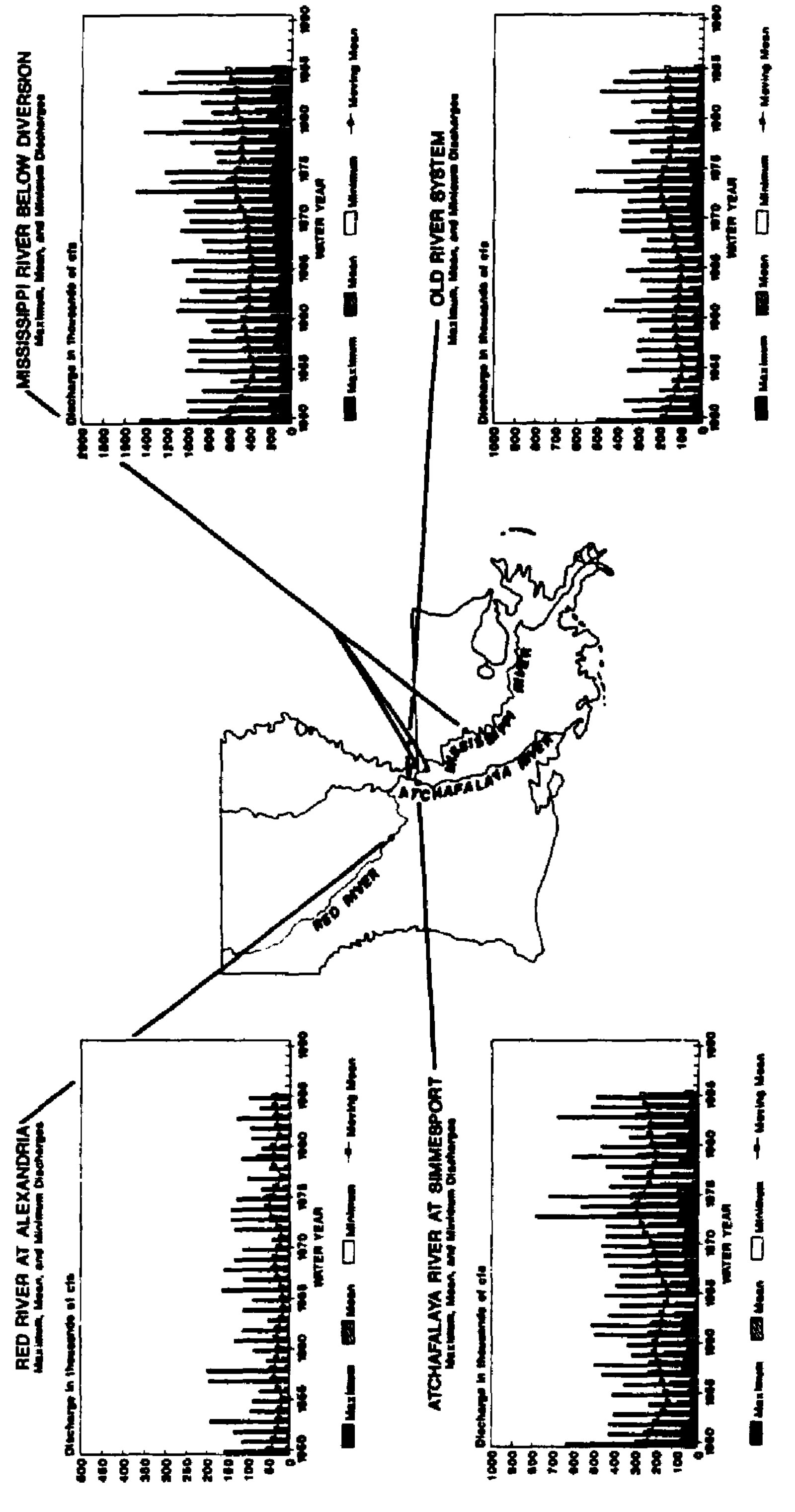


Figure 8. Maximum, mean, minimum discharges and 5-year moving averages of mean discharges at four locations on the Mississippi-Atchafalaya river system, 1950-1985.

Table 8. Results of tests for independence, trend, and randomness for discharges, suspended sediment loads, and suspended sediment concentrations.

H_0 :	INDEPENDENCE	TREND	RANDOMNESS
Mississippi			
Max Discharge	Not Significant	Not Significant	Not Significant
Mean Discharge	Highly Signif. (1%)	Not Significant	Not Significant
Mean Load	Highly Signif. (1%)	Highly Signif. (1%)	Not Significant
Mean Concentration	Highly Signif. (1%)	Highly Signif. (1%)	Significant (5%)
Red River			
Max Discharge	Not Significant	Not Significant	Not Significant
Mean Discharge	Not Significant	Not Significant	Not Significant
Mean Load	Not Significant	Not Significant	Not Significant
Mean Concentration	Not Significant	Significant (5%)	Not Significant
Old River System			
Mean Discharge	Highly Signif. (1%)	Significant (5%)	Significant (5%)
Mean Load	Not Significant	Not Significant	Not Significant
Mean Concentration	Significant (5%)	Highly Signif. (1%)	Not Significant
Atchafalaya			
Mean Discharge	Highly Signif. (1%)	Not Significant	Not Significant
Mean Load	Not Significant	Not Significant	Not Significant
Mean Concentration	Highly Signif. (1%)	Highly Signif. (1%)	Significant (5%)

Table 9. Flood frequency analysis for the period of investigation (1950-1985), using the Generalized Extreme Value (GEV), Three-Parameter Lognormal (3PLN), the Log Pearson Type III (LPT3), and the Wakeby (WKBY) probability distributions for the Mississippi below the diversion and the Red River at Alexandria. Maximum discharge in thousands of cfs.

MISSISSIPPI RIVER BELOW DIVERSION				RED RIVER AT ALEXANDRIA			
Return Period	GEV	3PLN	LPT3	GEV	3PLN	LPT3	WKBY
1.003	561	558	563	20.0	21.2	26.0	35.0
1.050	700	695	699	51.1	51.1	50.9	46.4
1.250	827	825	829	78.5	78.0	77.6	76.1
2.000	984	984	984	110	110	111	111
5.000	1170	1180	1170	146	146	147	145
10.000	1290	1290	1290	166	167	167	167
20.000	1390	1400	1390	182	186	183	188
50.000	1510	1530	1520	201	208	200	215
100.000	1590	1620	1610	213	224	211	235
200.000	1670	1710	1700	224	239	221	253
500.000	1760	1820	1820	236	259	232	276

Table 10. Maximum and mean discharge (in cfs), and corresponding rank by water year for the Mississippi below the diversion and the Red River at Alexandria (t indicates tie in rank).

	MISSISSIPPI RIVER BELOW DIVERSION				RED RIVER AT ALEXANDRIA			
Water Year	Max Q	Rank	Mean Q	Rank	Max Q	Rank	Mean Q	Rank
1950	1,458,000	3	699,700	2	157,000	6	56,740	3
1951	986,000	18	608,100	6	115,000	16	30,700	16
1952	1,011,000	16	539,400	10	137,000	9	23,200	19t
1953	852,000	29	384,000	27	192,000	3	34,400	14
1954	583,000	36	243,000	36	94,400	24	16,240	31
1955	1,022,000	14	365,200	30	89,800	26	20,200	25
1956	894,000	24	342,000	33	71,300	30	12,000	35
1957	994,000	17	473,600	16	196,000	2	45,970	7
1958	984,000	19	536,600	11	200,000	1	50,160	4
1959	765,000	33	356,100	31	55,200	33	18,700	27
1960	826,000	30	448,000	20	87,400	28	26,900	17
1961	1,107,000	10	460,000	17	134,000	11t	34,890	12
1962	1,081,000	11	524,900	12	113,000	18t	34,290	15
1963	881,000	25	286,100	35	51,800	34	13,680	32
1964	1,018,000	15	366,900	29	113,000	18t	11,480	36
1965	936,000	23	416,900	23	89,000	27	18,780	28
1966	1,154,000	7	370,500	28	165,000	4	22,050	22
1967	803,000	31	385,400	26	110,000	20	18,630	29
1968	861,000	27	433,900	22	159,000	5	44,220	8
1969	1,064,000	12	457,300	18	134,000	11t	40,590	10
1970	957,000	22	437,200	21	114,000	17	23,830	18
1971	973,000	21	388,100	25	43,000	36	13,460	33
1972	858,000	28	456,300	19	135,000	10	21,220	24
1973	1,498,000	1	729,000	1	142,000	7t	49,110	6
1974	1,117,000	9	623,000	5	142,000	7t	49,470	5
1975	1,220,000	5	558,000	9	129,000	13t	61,210	2
1976	717,000	35	396,000	24	68,000	31	19,960	26
1977	741,000	34	310,300	34	102,000	21	23,200	19
1978	977,000	20	506,700	13	50,000	35	12,290	34
1979	1,420,000	4	668,900	4	117,000	15	79,010	1
1980	1,050,000	13	493,800	14	66,000	32	22,590	21
1981	773,000	32	354,400	32	94,000	25	16,470	30
1982	873,000	26	491,900	15	96,000	23	34,800	13
1983	1,470,000	2	697,000	3	129,000	13t	40,100	11
1984	1,199,000	6	595,500	7	74,700	29	21,900	23
1985	1,128,000	8	560,000	8	97,900	22	43,900	9

The Old River system, i.e. Lower Old River or the Old River Outflow Channel or both combined, shows similarity to the Mississippi, particularly when comparing the patterns of the 5-year moving means (Fig. 8). The largest events, 1973, 1975, 1950, and 1983, correspond well with large discharges on the Mississippi. Mean discharges in the Old River system show highly significant serial dependence at the 1% level (Table 8). Trend is significant at the 5% level but not at the 1% level. Discharges have been increasing at a rate of approximately 1142 cfs annually. Mean discharges are also significantly non-random.

The Atchafalaya River also shows similar patterns to the Mississippi and Old River system, particularly when comparing the 5-year moving means (Fig. 8). The larger flood years, including 1973, 1975, 1983, and 1950, are nearly identical with the Old River system, and similar to the Mississippi. Mean discharges for the period of investigation show highly significant serial dependence at the 1% significance level, indicating influence from antecedent conditions (Table 8). Mean discharges are random and did not display significant trend.

Overall, the discharges on the Mississippi are dominant in the system and strongly affect discharges on the Old and Atchafalaya rivers (Fig. 8). Mean discharges on the Mississippi below the diversion are about twice those on the Atchafalaya, about three times that of the Old River system, and generally over ten times that of the Red River. The Red River discharges consequently do not strongly influence discharges on the Atchafalaya in most years.

Suspended sediment load and concentration means and trends

The rivers in the study area show trends in suspended sediment load and concentration, although they have slightly different periods of record. Mean annual sediment loads and concentrations of the Mississippi River below the diversion, show a sharp decline since the 1950s, even though more recent years include several high discharges (Fig. 9). Factors that may contribute to this decrease include dams, revetments, and land use changes upstream in the basin. The trends are significant at the 1% significance level for both suspended load and concentration. The trends are decreasing an average of 15,888 tons/day and 13 mg/l annually. Mean loads and concentrations also display highly significant serial dependence. Mean suspended loads are significantly random, however, mean suspended sediment concentrations were not.

Mean sediment loads and concentrations on the Red River at Alexandria show large variations over the period of investigation (Fig. 9). The mean load does not show significant trend, however, the mean concentration shows trend significant at the 5% level. The trend in concentration has been decreasing 24 mg/l annually between 1952 and 1980. A sharp decline begins in 1975 and suggests some form of intervention upstream. The cause of this trend is probably related to cumulative effects of dams, revetments, and land use changes in the basin. Mean loads and concentrations do not display significant serial dependence. Mean loads and concentrations are also significantly random.

Mean sediment loads and concentrations in the Old River Outflow Channel, for a shorter period of record, show declining values, although the trend of the mean load is not significant. The trend proves to be highly significant for concentration at the 1% significance level, with decreasing values since 1964 of about 8 mg/l annually. Mean loads do not display significant serial dependence, however, mean concentrations show serial dependence at the 5% significance level. Mean loads and concentrations are also significantly random.

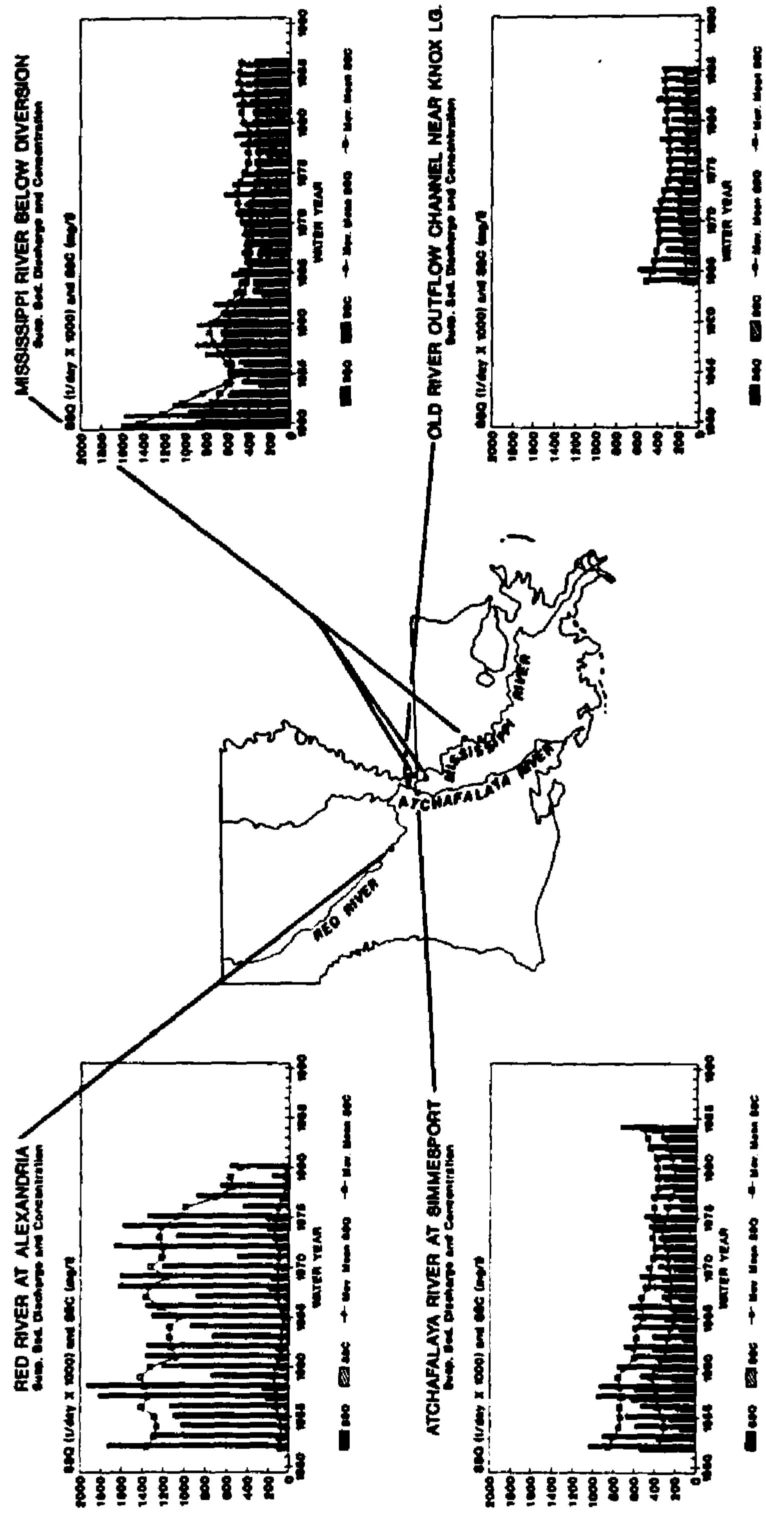


Figure 9. Mean suspended sediment loads and concentrations and 5-year moving averages at four locations on the Mississippi-Atchafalaya river system, 1950-1985.

Mean sediment concentrations in the Atchafalaya show a decreasing trend since water year 1952, related to changes in the sediment concentrations of its sources (Fig. 9), although mean loads do not show significant trend. The trend in concentration is decreasing 14 mg/l annually for the period between 1952 and 1985. Mean loads do not display significant serial dependence. Mean concentrations display highly significant serial dependence at the 1% significance level. Mean loads are significantly random, whereas mean concentrations are not.

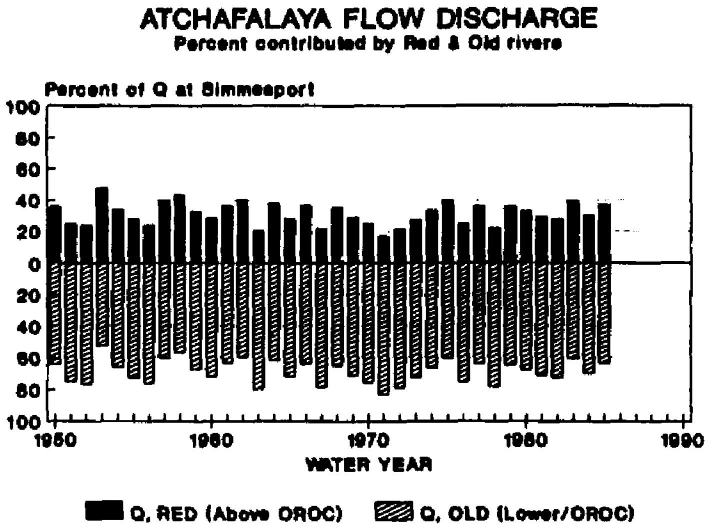
Overall, mean annual loads are over twice as great on the Mississippi as on the Atchafalaya for the early part of the period of investigation, and less than twice as great for the latter part of the period of investigation (Fig. 9). Suspended loads on the Mississippi are about three times that of the Old River Outflow Channel for the period where data are available in the latter part of the period of investigation. Mean annual loads are as few as four and as many as ten times greater on the Mississippi than the Red for the period of investigation.

Suspended sediment concentrations show both temporal and regional differences in the four rivers (Fig. 9). The Red River has highest concentrations for every year over the period of record, generally exceeding the Mississippi and Old rivers by two to five times. The differences are attributed to the greater sediment yields in semiarid as compared to humid climates because of differences in vegetation and soil erosion potential (Langbein and Schumm, 1958; Fournier, 1960; Douglas, 1967; Walling and Kleo, 1979; Dunne, 1979; Hadley et al., 1985). Mean annual suspended sediment concentrations are typically lowest in Old River, but in some years are lowest in the Mississippi. The Atchafalaya, receiving some flow from the Red River and most from the Mississippi through Old River, shows mean suspended sediment concentrations intermediate to both rivers but generally closer to the Mississippi and Old rivers than the Red River.

Discharge and suspended sediment components of the Atchafalaya

Discharges from the Old River system, i.e., Lower Old River or the Old River Outflow Channel or both combined, provides about 50 to 85% of the flow of the Atchafalaya River for various water years between 1950 and 1985, and average 68.9% over this period (Fig. 10). The Red River, computed as the remaining percent, accounts for 15 to 50% of the Atchafalaya River flow, averaging 31.1% over this period (Fig. 10).

The annual suspended load contribution of Old River system presently ranges from about 30% to 90% of the annual suspended load of the Atchafalaya at Simmesport, and therefore shows a wider range than the flow (Fig. 10). That of the Red River above the Old River Outflow Channel, computed as the remainder, provides about 10% to 70% of the Atchafalaya's load (Fig. 10). The annual suspended load provided by the Old River system for the 1964 to 1986 period averages 58.0%, whereas that provided by the Red River averages 42.0%. In some years, the Red River provides minor contributions of suspended sediment load to the Atchafalaya, whereas in other years it is the dominant component of the suspended sediment load. Assessment of discharge-sediment relationships in the Atchafalaya are thus incomplete without examining the spatial and temporal variations of these parameters in the Red River.



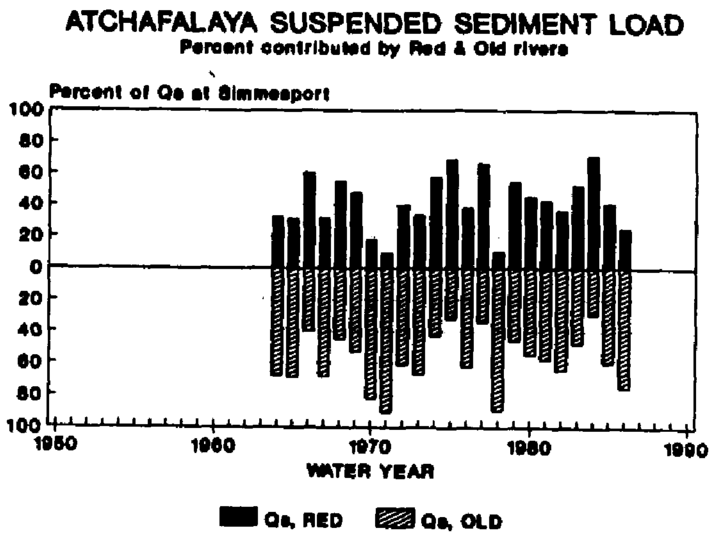


Figure 10. Atchafalaya River discharge and suspended sediment load as a percent of the Red River and Old River system, 1950-1985.

SYSTEM BEHAVIOR INTERPRETED ON THE BASIS EMPIRICAL RELATIONSHIPS: NONLINEARITY AND PHYSICAL EXPLANATIONS

Some interpretations of processes and spatial differences in the Mississippi-Atchafalaya system can be made from analysis of empirical relationships of discharge and suspended sediment. The locations of primary interest are the Mississippi River below the diversion (1950-87) and the Red River at Alexandria (1963-87) because they provide flow and sediment to the other locations. The Old River Outflow Channel at Knox Landing (1963-87) and the Atchafalaya River at Simmesport (1950-87) are fed exclusively or principally from the Mississippi River. The Mississippi River at Belle Chasse (1977-88) serves to test whether the behavior of suspended sediment with discharge is different than upstream because of the greater amount of silt and clay locally in the bed material.

Empirical relationships between discharge and sediment on Mississippi below Old River diversion

The Mississippi River below the diversion shows a nonlinear relationship between discharge and suspended sediment concentration (Fig. 11; Table 11). Generally speaking, concentrations increase sharply with discharges in the lower discharge range, are fairly uniform for intermediate discharges, and decrease somewhat with higher discharges. Hence, quadratic log-log relationships offer a better fit to the data than the linear log-log relationships (Tables 11 and 12). The plot and function are concave-downward.

The nonlinear form of the function between suspended sediment and discharge largely relates to the nonlinear form of its dominant component, the silt-clay concentration. The suspended silt-clay concentration also initially increases as discharge increases, levels, but then decreases more sharply than the suspended sediment concentration at the highest discharges. Data therefore more closely follow the quadratic log-log functions than the linear log-log models (Table 11), and the model form is concave-downward. The absolute value of the quadratic coefficient is greater than for the suspended sediment because of the sharper decrease at higher discharges.

Suspended sand concentration also shows nonlinearity with discharge, but follows a very different function over the discharge range sampled than the suspended sediment and silt-clay concentration. The plots and functions for the Mississippi River below the diversion initially show rapidly rising concentrations with increasing discharges followed by leveling for intermediate and highest discharges. Suspended sand shows a stronger correlation and steeper slope with discharge using a linear relationship than the suspended sediment and silt-clay concentration (Fig. 11; Table 11). Quadratic log-log functions improve correlations somewhat as the graph and model shows a concave-downward curvilinear form (Fig. 11; Table 11). The absolute value of the quadratic coefficient is lower than for suspended sediment and silt-clay concentration (Table 11).

The suspended sediment load on the Mississippi below the diversion rises rapidly for low discharges, then increases more slowly with increasing discharges in the intermediate discharge range, and stabilizes at the highest discharges (Fig. 11). Correlations improve with a quadratic log-log function, since the graph shows a concave-downward curvilinear form (Tables 11 and 12). The better-explained variance compared to that of concentration and discharge is a likely result of the definition of load as the product of discharge and concentration. It can be seen here, and with succeeding examples (Table 11), that the regressions with suspended load change and typically improve the correlations of discharge and concentration, and introduce appreciable biases.

As with the sand concentration, the percentage of sand in suspension generally increases throughout the discharge range on the Mississippi below the diversion (Fig. 11). Data show great scatter, with large ranges of percentages throughout the discharge range. Use of a quadratic log-log function does not improve the explanation of the variance appreciably. The model's form, unlike the concentration parameters, is concave-upward and shows appreciably different coefficients than the other parameters because the ordinate is not logarithmically transformed (Tables 11 and 12).

Using the F^* statistic, the quadratic models are significantly different than the linear models for all parameters examined on the Mississippi River below the diversion (Table 12). The use of the quadratic approach is also justified in that the quadratic coefficients (Table 11) are all statistically significant.[3] The sand concentration stabilizes at the highest discharges, while the silt-clay concentrations decline, which causes the combined or total concentration to decline. Two factors that may explain why these relationships are nonlinear and quadratic are that the availability of specific sediment size fractions may be reduced at higher discharges, and that velocity may be nonlinear, increasing less rapidly at higher discharges and causing a reduction in sediment transport at higher discharges.

The nonlinearity of suspended silt-clay concentration appears to be related to its limited local availability in the bed material and the manner in which it is transported to the channel. After the most readily erodible sediments on the soil surface and in tributaries are initially flushed by the snowmelt and early spring runoff and after the local supplies of sediment around the channel perimeter are mobilized by increasing flows, the rate at which material can be input to the system decreases. Hysteresis effects may occur if discharges continue to rise and continued runoff results in declining concentrations in the water. Identification of hysteresis requires extensive time series observations, which are presented in the following section. To a lesser extent, the suspended sand transport might also decline somewhat at higher discharges, in that the more loosely consolidated and unstable material around the channel perimeter will be removed on the rising stage of the hydrograph, resulting in hysteresis effects.

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[3] As with many statistical relationships, the error terms or residuals may be serially correlated or autocorrelated. The existence of hysteresis also suggests that there is serial autocorrelation in the data (Naden, 1988). Addition of the quadratic term may result in intercorrelation or multicollinearity and may enhance autocorrelation. Details of these problems are discussed in Neter et al. (1983), although such corrections are not made herein. The effect of correcting for such conditions may change the t and F statistics. Thus, caution should be taken in accepting the quadratic relationships, particularly when the statistics are not well above the significance level.

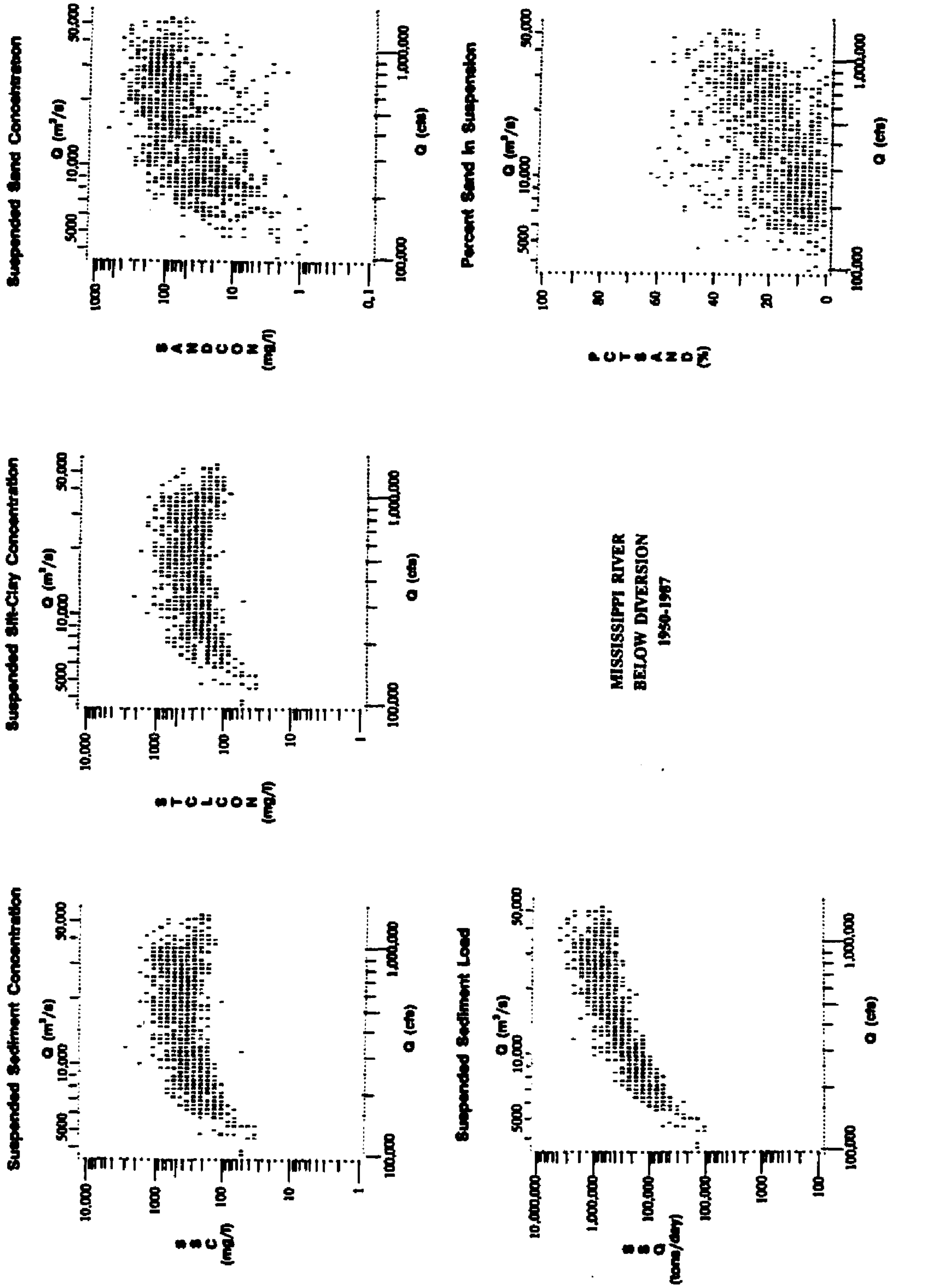

Figure 11. Scattergrams showing relationships between discharge and suspended sediment variables for the Mississippi River at Baton Rouge-Red River Landing-Tarbert Landing, 1950-87.

Table 11. Regression statistics of discharge (log) with suspended sediment concentration (log), suspended silt-clay concentration (log), suspended sand concentration (log), suspended sediment load (log), and percentage sand in suspension. Number of samples given for % sand equals zero or missing, % sand equals zero, and all samples. Coefficients of determination for both the linear and quadratic models are shown, along with the y-intercept (B_0), linear slope coefficient (B_1) and quadratic coefficient (B_2) for five variables. An asterisk (*) indicates that the t-statistic is significant at the 5% level.

RIVER AND LOCATION; LOGQ VS.:

Linear	R^2	B_0	B_1	t	Quadratic	R^2	B_0	B_1 B_2	t t
Mississippi River below diversion (1950-1987; n = 1111/1117/1122)									
LOGSS	0.23	-0.22	0.48	18.5*		0.40	-51.5	18.8 -1.62	18.0* -17.5*
LOGSTCL	0.14	0.32	0.37	13.4*		0.33	-54.4	19.9 -1.73	18.0* -17.6*
LOGSDCO	0.32	-4.53	1.10	22.9*		0.35	-43.5	15.0 -1.23	6.99* -6.48*
LOGSSEDQ	0.74	-2.79	1.48	56.9*		0.80	-54.1	19.8 -1.62	18.9* -17.5*
PCTSAND	0.19	-104	21.9	16.1*		0.20	561	-215 21.0	-3.53* 3.89*
Mississippi River at Belle Chasse (1977-1988; n = 98/103/103)									
LOGSS	0.58	-5.01	1.28	11.8*		0.60	-41.2	14.1 -1.13	2.75* -2.50*
LOGSTCL	0.46	-4.18	1.12	9.30*		0.52	-56.6	19.7 -1.64	3.55* -3.34*
LOGSDCO	0.67	-12.1	2.23	14.0*		0.72	73.0	-27.8 2.66	-3.79* 4.11*
LOGSSEDQ	0.81	-7.58	2.28	21.0*		0.82	-43.7	15.1 -1.13	2.95* -2.50*
PCTSAND	0.31	-154	29.9	6.77*		0.47	2731	-993 90.4	-5.27* 5.43*

Table 11 (cont.). Regression statistics of discharge (log) with suspended sediment concentration (log), suspended silt-clay concentration (log), suspended sand concentration (log), suspended sediment load (log), and percentage sand in suspension. Number of samples given for % sand equals zero or missing, % sand equals zero, and all samples. Coefficients of determination for both the linear and quadratic models are shown, along with the y-intercept (B_0), linear slope coefficient (B_1) and quadratic coefficient (B_2) for five variables. An asterisk (*) indicates that the corresponding t-statistic is significant at the 5% level.

RIVER AND LOCATION; LOGQ VS.:

Linear	R^2	B_0	B_1	t	Quadratic	R^2	B_0	B_1 B_2	t t
Red River at Alexandria (1963-1987; n = 511/511/511)									
LOGSS	0.74	-1.05	0.86	38.5*		0.74	-1.40	1.02 -0.02	2.46* -0.40
LOGSTCL	0.73	-1.11	0.84	37.1*		0.73	-0.71	0.66 0.02	1.54 0.44
LOGSDCO	0.53	-2.39	0.99	23.9*		0.53	-4.79	2.12 -0.13	2.74* -1.46
LOGSSEDQ	0.93	-3.62	1.86	83.5*		0.93	-3.97	2.02 -0.02	4.87* -0.40
PCTSAND	0.01	9.23	2.83	2.41*		0.02	-110	59.0 -6.53	2.71* -2.58*
Old River near Knox Landing (1963-1987; n = 604/617/617)									
LOGSS	0.27	0.31	0.41	15.2*		0.30	-7.89	3.70 -0.33	5.59* -4.97*
LOGSTCL	0.19	0.73	0.31	11.9*		0.27	-11.8	5.34 -0.50	8.62* -8.12*
LOGSDCO	0.28	-3.75	1.01	15.4*		0.29	-43.5	-3.39 0.44	-2.11* 2.74*
LOGSSEDQ	0.82	-2.25	1.41	52.1*		0.82	-10.46	4.70 -0.33	7.10* -4.97*
PCTSAND	0.16	-74.5	17.6	10.8*		0.23	668	-279 29.6	-7.23* 7.69*

Table 11 (cont.). Regression statistics of discharge (log) with suspended sediment concentration (log), suspended silt-clay concentration (log), suspended sand concentration (log), suspended sediment load (log), and percentage sand in suspension. Number of samples given for % sand equals zero or missing, % sand equals zero, and all samples. Coefficients of determination for both the linear and quadratic models are shown, along with the y-intercept (B_0), linear slope coefficient (B_1) and quadratic coefficient (B_2) for five variables. An asterisk (*) indicates that the corresponding t-statistic is significant at the 5% level.

RIVER AND LOCATION; LOGQ VS.:

Linear	R^2	B_0	B_1	t	Quadratic	R^2	B_0	B_1 B_2	t t
Atchafalaya River at Simmesport (1950-1987; n = 981/998/1026)									
LOGSS	0.29	-0.26	0.53	20.4*		0.35	-18.8	7.71 -0.69	10.9* -10.2*
LOGSTCL	0.19	0.30	0.41	15.2*		0.29	-21.5	8.82 -0.81	12.5* -11.9*
LOGSDCO	0.42	-4.49	1.17	26.4*		0.42	-11.0	3.68 -0.24	2.98* -2.04*
LOGSSEDQ	0.77	-2.83	1.53	58.4*		0.79	-21.4	8.71 -0.69	12.3* -10.2*
PCTSAND	0.28	-97.5	21.8	19.6*		0.23	559	-232 24.5	-7.66* 8.38*

Table 12. Comparison of linear and quadratic regression models for discharge (log) with suspended sediment concentration (log), suspended silt-clay concentration (log), suspended sand concentration (log), suspended sediment load (log), and percentage sand in the suspended load. Number of samples given for % sand equals zero or missing, % sand equals zero, and all samples. Model statistic and the probability are given for these five variables. An asterisk (*) indicates the corresponding statistic is significant at the 5% level.

RIVER AND LOCATION; LOGQ VS.:									
LOGSS		**LOGSTCL**		**LOGSDCO**		**LOGSSEDQ**		**PCTSAND**	
F*	**p**	**F***	**p**	**F***	**p**	**F***	**p**	**F***	**p**
Mississippi River below diversion (1950-1987; n = 1111/1117/1122)									
306.76	0.001*	311.21	0.001*	42.01	0.001*	306.76	0.001*	15.17	0.001*
Mississippi River at Belle Chasse (1977-1988; n = 98/103/103)									
6.26	0.025*	11.19	0.001*	16.89	0.001*	6.26	0.025*	29.50	0.001*
Red River at Alexandria (1963-1987; n = 511/511/511)									
0.158	>0.10	0.194	>0.10	2.136	>0.10	0.158	>0.10	6.66	0.010*
Old River Outflow Channel near Knox Landing (1963-1987; n = 604/617/617)									
24.70	0.001*	65.93	0.001*	7.53	0.010*	24.70	0.001*	59.09	0.001*
Atchafalaya River at Simmesport (1950-1987; n = 981/998/1026)									
103.29	0.001*	141.18	0.001*	4.15	0.050*	103.29	0.001*	70.26	0.001

Another possible cause for the nonlinearity of suspended sediment concentration and discharge could be related to the nonlinearity demonstrated elsewhere in studies of at-a-station hydraulic geometry. These studies have shown concave-downward log-log velocity-discharge curves and concave-upward log-log depth discharge curves[4] in several rivers in the United States and England and in flume studies (Richards, 1973; 1977) (Fig. 12). The nonlinear changes of velocity with discharge are interrelated with discontinuities in depth-discharge relationships that occur following the transition from lower to upper flow regime (Dawdy, 1961), and are largely associated with bedform variations with this transition (Simons and others, 1961; 1966). Physical changes such as these produce nonlinear changes of roughness with discharge as identified by Church (1967) and described in detail by several others (Richards, 1973, 1977; Knighton, 1979).

Similarly, hydraulic changes including discontinuities and deceleration in velocity could be associated with the transition from below- to above-bankfull flows. Although this phenomena has not been given much specific attention, significant hydraulic changes may occur in the transition from channel confinement to dispersal of part of the flow across the floodplain surface. Such effects might exist in the Mississippi-Atchafalaya system but are probably not as pronounced as in other rivers, because the system is largely confined within artificial levees and has not been allowed to spread across its floodplain since levee improvements following in flood of 1927.

Discontinuities do not show up as well-defined thresholds in natural streams, consequently continuous curves best fit the behavior of the variables involved (Richards, 1973). If such discontinuities exist, changes in velocity would certainly principally affect the bed material load and thus would be manifest principally in the sand component. However, in areas where there are significant local sources, nonlinear changes in velocity associated either with bankfull, bedform or other transitions may also affect the fine component.

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[4] Some of the same circumstances causing higher correlations between suspended load and discharge are also manifest in relationships of discharge and velocity. Discharge is a product of velocity and the channel cross-sectional area, also known as the continuity equation.

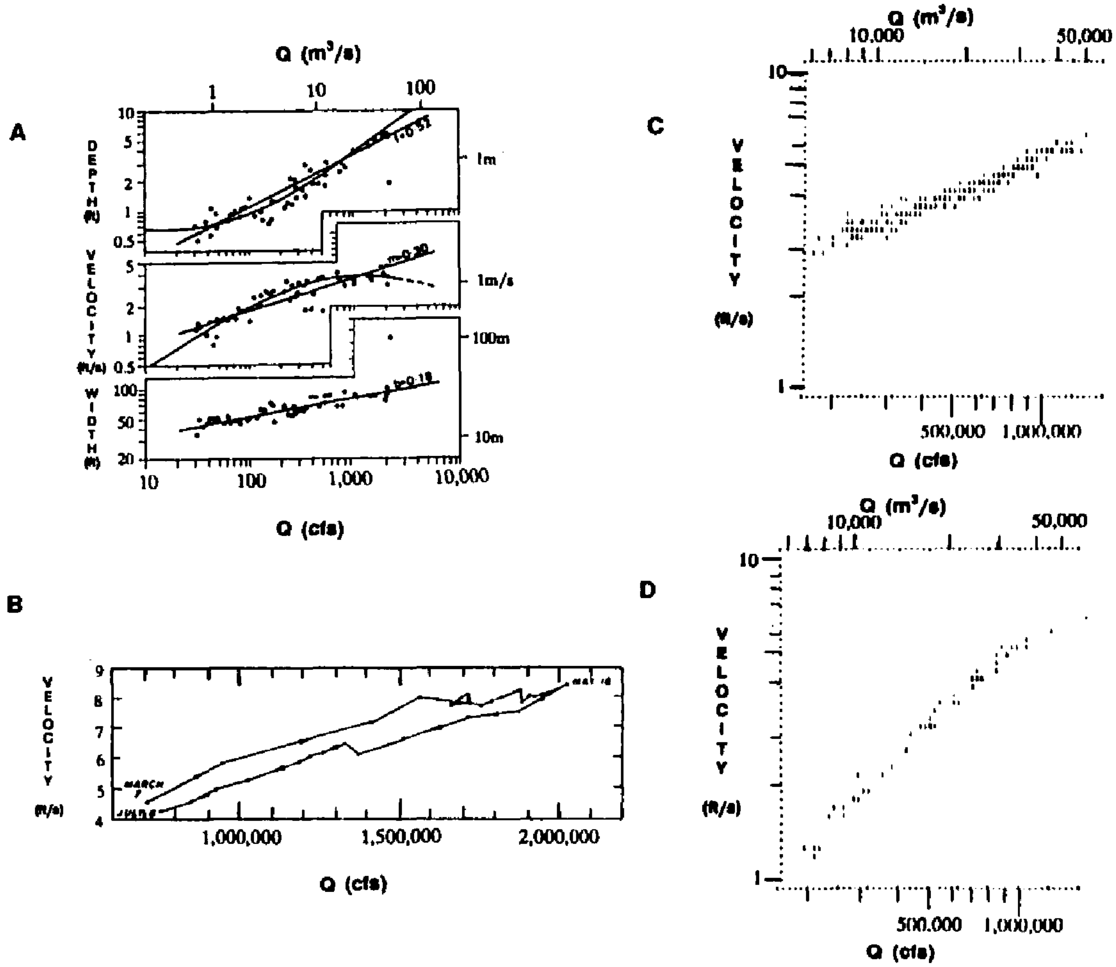


Figure 12. Results of discharge-velocity relationships elsewhere and in the Mississippi River: a) for Seneca Creek, Dawsonville, Maryland modified from Leopold, Wolman, and Miller (1964) and from Richards (1973); b) from Robbins (1977) at Natchez for 1973; c) for the Mississippi at Tarbert Landing from 1978-1986 on dates of suspended sediment sampling; d) for the Mississippi at Belle Chasse from 1978-1986 on dates of suspended sediment sampling (Data source for 12c and d: New Orleans District, 1978 to 1986).

While nonlinear discharge-velocity changes might induce nonlinear discharge-suspended sediment relationships, most empirical evidence does not seem to support that the phenomena of decelerating velocities at high discharges exists in the Mississippi River. At extremely high discharges, a leveling or decrease in velocity may take place during specific events such as the 1973 flood graphed by Robbins (1977) (Fig. 12b), but a much larger number of measurements over a long time period would be required to demonstrate whether there is significant nonlinearity. Furthermore, to be compared with previous studies and with suspended sediment would require graphing velocity against discharge on a log-log scale as done by Richards (Fig. 12a). A more comprehensive, but still preliminary, analysis of empirical data over nearly a 10-year period instead indicates that the relationship between discharge and velocity at the Mississippi River below the diversion is linear (Fig. 12c and d). Discharge-velocity relationships are clearly worthy of further study, although with present data it seems unlikely that velocity decreases or increases more slowly at higher discharges.

The scatter in discharge-suspended sediment relationships at the Mississippi River below the diversion is appreciable, but can be explained by several factors including trend or nonstationarity and hysteresis effects. The trend or nonstationarity of the system is documented in the previous chapter, as the mean suspended sediment concentration shows statistically significant declining trends and statistical evidence shows that the mean discharges have not declined concomitantly. Hysteresis effects have been described in other studies and will be explored in greater detail in the following chapter.

Empirical relationships between discharge and sediment on Mississippi River at Belle Chasse

Suspended sediment sampling on the Mississippi River at Belle Chasse includes appreciably fewer measurements than at the Mississippi River below the diversion, however, it includes at least two of the largest events in 1979 and 1983 and some of the lower discharge years including 1981 and 1988. The lowest concentrations in the study area, with values of 7 mg/l during the July 1988 drought, are measured at this site.

Quadratic log-log relationships for suspended sediment and silt-clay concentration are concave-downward and show improved correlations over the linear log-log relationships (Tables 11 and 12). The form of the function between suspended sediment and discharge is similar to that of the silt-clay concentration with discharge (Fig. 13). Concentrations generally increase rapidly at first, and then level as discharge increases. The absolute value of the quadratic coefficient is greater for the silt-clay than for the total suspended sediment concentration, related to a greater downturn in the silt-clay component at higher discharges (Table 11).

The quadratic relationship for sand concentration and discharge is concave-upward and the graph appears to follow a more complex polynomial form than previous examples (Figs. 11 and 13; Table 11). At the lowest discharges, the relationship between sand concentration and discharge shows a decrease with increasing discharges. At intermediate and high discharges, sand concentration increases with increasing discharges, and then appears to level at highest discharges.

Suspended sediment load at Belle Chasse rises rapidly as discharge increases throughout the range (Fig. 13). The relationship of suspended sediment load and discharge is linear, and the explanation of the variance is much greater than for the relationship of concentration with discharge, for reasons described previously (Table 11). The correlation does not show appreciable improvement with application of a quadratic log-log function (Table 12).

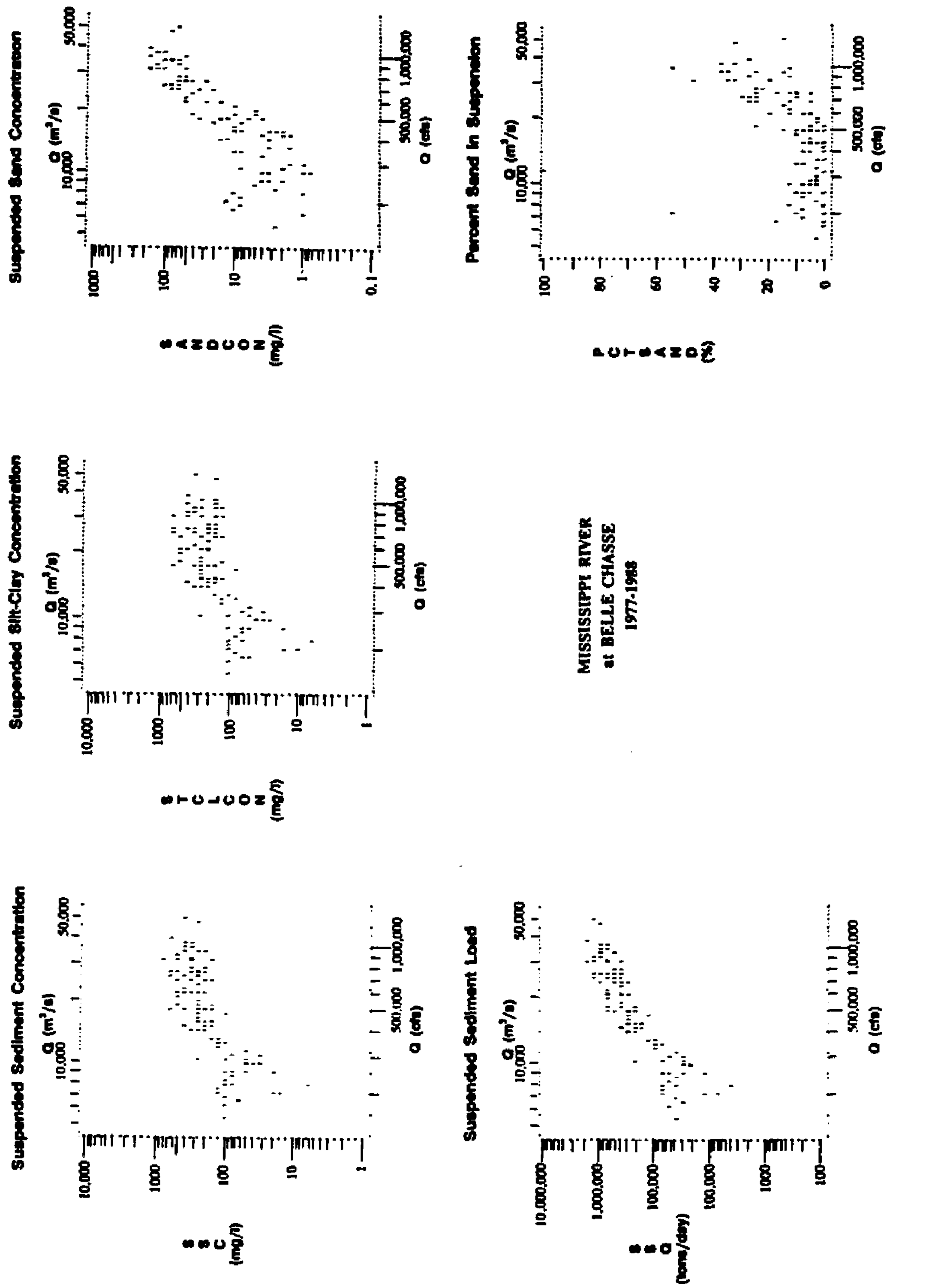


Figure 13. Scattergrams showing relationships between discharge and suspended sediment variables for the Mississippi River at Belle Chasse, 1977-88.

The plots for the percentage of sand in suspension and discharge at Belle Chasse are concave-upward and curvilinear. At low discharges, percentages decrease with increasing discharges and then at higher discharge percentages steeply increase with increasing discharges. Therefore, the model fit improves appreciably with the application of a quadratic log-log function. The amount of scatter is generally highest at high discharges because the maximum sand percentages and thus the potential for variability are greater.

The quadratic models improve the correlations over the linear models and are significant or highly significant for all parameters examined using the F^* statistic (Table 12). The quadratic coefficients are also statistically significant, indicating the quadratic models are justified. The explanation of the variance for both the linear and quadratic models is much better than its upstream counterpart for several reasons, including that the plots and models show reduced scatter downstream. As mentioned before, the shorter period of record reduces the effects of trends, which are statistically significant in the Mississippi, and therefore should show less scatter.

The models for the Mississippi at Belle Chasse and below the diversion also show different forms because of changes in hydraulic factors from upstream to downstream, and the increased availability of silt and clay from the bed. Compared to upstream, Belle Chasse shows lower suspended sediment and silt-clay concentrations at low discharges despite an abundance of silt-clay sediment sizes available from the bed (Fig. 5). This confirms the findings of Everett (1971), Wells (1980), and Meade (1987) who found that at less-than-average discharges, suspended sediment concentrations decreased downstream.

The physical explanation for this decrease was not explored, however, although it seems intuitive from application of the continuity equation. For a given discharge, velocity would decrease downstream as the cross-sectional area increases, owing to deepening of the channel and thalweg downstream, particularly when stages along the reach are low (Fig. 5). The water surface gradient along the study reach, computed as the difference in stage elevations at upstream and downstream locations over a given length of channel, also becomes steeper with increasing discharges, as seen in the comparison of stage elevations for low water vs. bankfull flow (Table 4). The differences in cross sectional area between upstream and downstream locations are therefore large at low discharge and become much smaller during high discharges (Fig. 14), supported by a preliminary analysis of data from Stages and Discharges of the Mississippi River and Tributaries (New Orleans District, 1978-1986).

The same data source shows that at low discharges the velocities are lower than upstream (Fig. 12c and d). At higher discharges, however, the velocities for a given discharge at both the upper and lower sections of the study area are of comparable magnitude (Fig. 12c and d). Belle Chasse typically shows similar silt-clay and total concentrations at high discharges as upstream (Figs. 11 and 13), and not tremendously greater concentrations as indicated by Meade (1987) (Fig. 5). Downstream, where fines become increasingly abundant on the bed, they are introduced into the water column by resuspension. Upstream, fine material is not as plentiful on the bed and thus resuspension is not a major mechanism for providing fine material.

Belle Chasse also shows much lower suspended sand concentrations at low and intermediate discharges compared to upstream. The reasons for the downstream decrease include the hydraulic changes and reduced velocities for similar discharges and the reduced availability of sand in the bed material compared to upstream. The Impact Law and Stoke's law, which describe settling velocities of particles greater than and less than 0.1 mm in diameter, respectively, (Rubey, 1933; Schreiber, 1978), imply that as velocities are decreasing sands, silts, and clays settle in succession, producing a fining-upward bed surface, at least in localized areas. Low discharges, low velocities, and low availability of sand therefore may be interdependent and coexistent. Once this silt-clay blanket is removed as discharges increase, the sand beneath becomes exposed and is subject to transport by high discharges. Differences in sand concentration between the upstream and downstream stations are not as pronounced at high discharges, because of comparable velocities and increased availability of sand as characterized by these interrelationships.

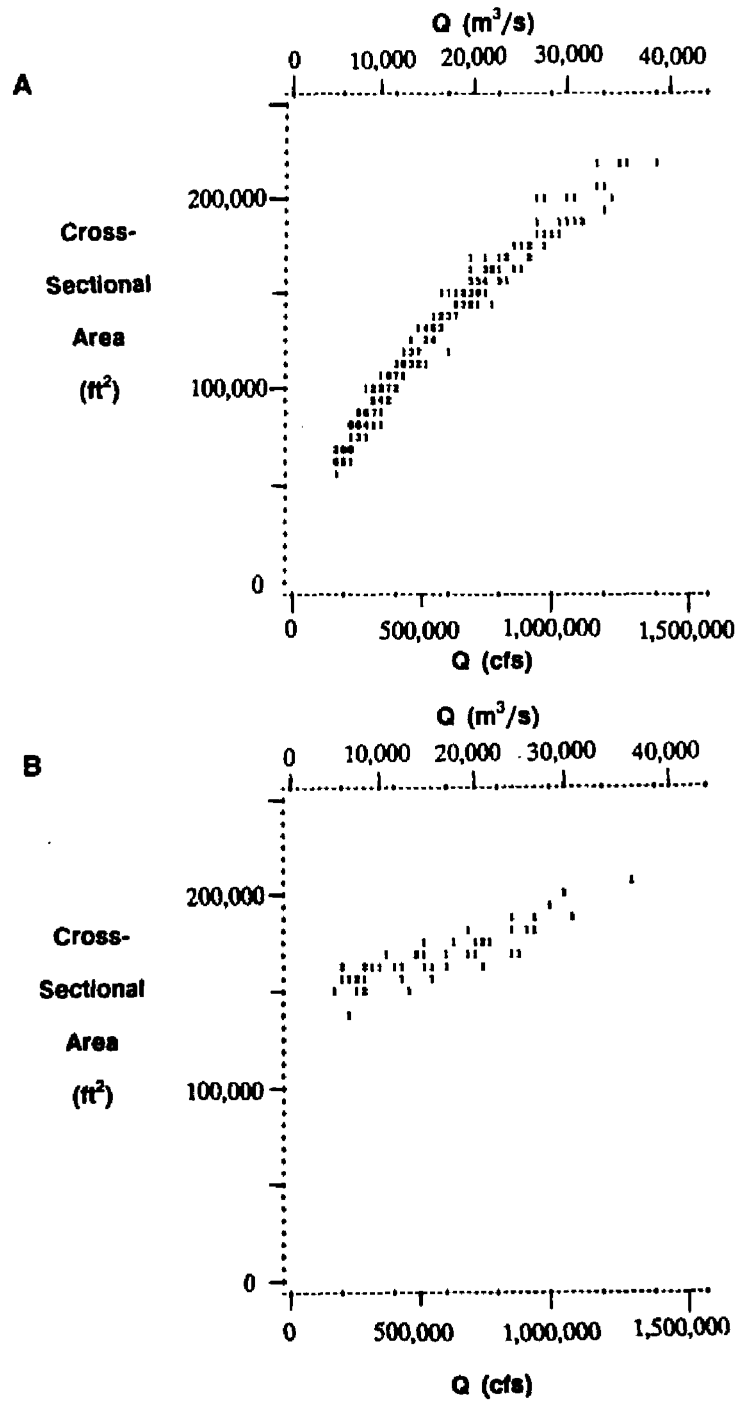


Figure 14. Relationships between discharge and cross-sectional area on the lower Mississippi River in the study area on dates of suspended sediment sampling: a) for the Mississippi at Tarbert Landing from 1976-1986; b) for the Mississippi at Belle Chasse from 1978-1986 (Data source: New Orleans District, 1976 to 1986).

Empirical relationships between discharge and sediment on the Red River at Alexandria

Suspended sediment and silt-clay concentrations on the Red River at Alexandria show the strongest linear relationships of the rivers and sampling locations in the study area (Fig. 15; Table 11). Maxima are in excess of 5000 mg/l. Total suspended sediment and silt-clay concentrations generally increase rapidly throughout the range of discharges. The model fit and coefficients of the quadratic relationship are not significant (Tables 11 and 12).

Since suspended sand concentration increases rapidly throughout the range of discharges, it also shows a fairly strong linear relationship with discharge (Fig. 15; Table 11). This relationship shows a slightly steeper slope and more scatter than the suspended sediment and silt-clay components. The explanation of the variance is therefore lower. The quadratic model fit and coefficients are not significantly improved over that found with application of a linear relationship (Tables 11 and 12).

Suspended sediment load increases with increasing discharge, and shows a very strong linear relationship. Because of its high concentrations, the Red River at highest discharges has suspended sediment loads comparable to that on the Mississippi River below the diversion (Figs. 11 and 15). The slope of the relationship between discharge and suspended sediment load is steeper than for the other parameters, a result of the definition of load as the product of discharge and concentration. Correlations are similar with the application of a quadratic log-log function.

The percentage of sand in suspension shows tremendous scatter throughout the discharge range (Fig. 15), with most scatter in the intermediate discharges. Sand percentages do not show an increase with increasing discharges, perhaps because the proportion of available sand does not outweigh the available silt-clay in the basin and channel perimeter. The relationship between the percentage of sand in suspension and discharge is neither linear, nor quadratic.

The quadratic regression model does not prove to be significantly different from the linear model using the F* statistic for most parameters on the Red River at Alexandria except for percentage sand in suspension, which in turn is not well-explained by the regression models. The explanation of the variance for the other parameters using both the linear and quadratic models is good, possibly because silt and clay are abundant in the basin and/or along the channel perimeter, and therefore does not show a decline at high discharges.

The large concentrations in the Red compared to the Mississippi may be explained by hydraulic properties such as velocity and temperature amongst other factors (Table 1), climate, geology, dams, land use, and the extent of bank protection. The Red River drainage basin is dominantly semiarid, with less dense vegetation cover than in the humid Mississippi basin. As described previously, such semiarid basins tend to produce greater sediment volumes per unit area than humid basins. The basin geology may also influence erosion rates, and large areas of the Mississippi basin contain metamorphic rock and calcareous sedimentary rocks which do not typically provide large sediment yields. Throughout the Mississippi basin, dams have trapped large quantities of sediment over the years. Greater urbanization in the Mississippi basin, such that much of the surface is covered with concrete also results in decreased sediment yields in the Mississippi River. Revetments are also not as extensive on the Red as on the Mississippi, which allows for increased supply of sediment from bank caving and elsewhere around the channel perimeter.

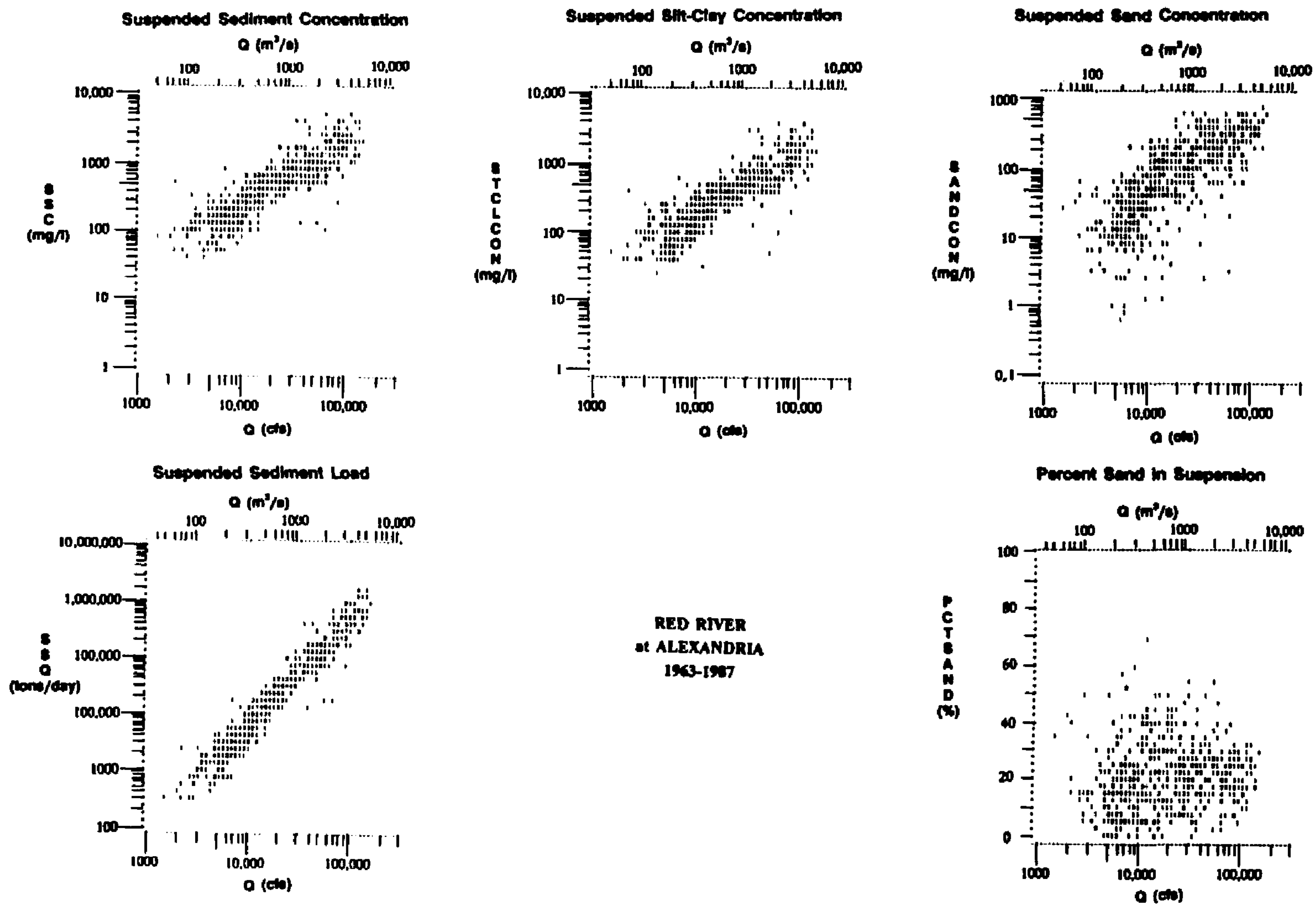


Figure 15. Scattergrams showing relationships between discharge and suspended sediment variables for the Red River at Alexandria, 1963-87.

Empirical relationships between discharge and sediment on the Old River Outflow Channel

The Old River Outflow Channel, which receives its flow from the Mississippi River, also shows a nonlinear relationship between discharge and the suspended sediment and silt-clay concentration (Figs. 16; Table 11). Concentration generally increases sharply with discharges in the lower discharge range, stabilizes for intermediate discharges, and decreases somewhat with higher discharges. Hence, quadratic log-log relationships offer a better fit to the data than the linear log-log relationships, and the plots are concave-downward (Table 12). The absolute value of the quadratic coefficient for silt-clay concentration is larger than for suspended sediment because the silt-clay concentration shows greater decreases at higher discharges.

Suspended sand concentration on the Old River Outflow Channel generally shows a more strongly linear relationship and correlation with discharge on the main system than suspended silt-clay or total suspended sediment concentration (Fig. 16; Table 11). Sand concentration rises steadily throughout the discharge range. Quadratic log-log functions produce minimal changes in correlation (Tables 11 and 12). The function is concave-upward, although it shows a small quadratic coefficient coefficient.

The suspended sediment load rises rapidly throughout the discharge range, but stabilizes or shows a slight down-turn for the highest discharges (Fig. 16). Correlations improve with a quadratic log-log function, although the improvement is not appreciable because the down-turn constitutes only a small portion of the graph. As with the other locations, use of suspended sediment load rather than concentration, produces much higher correlations (Table 11).

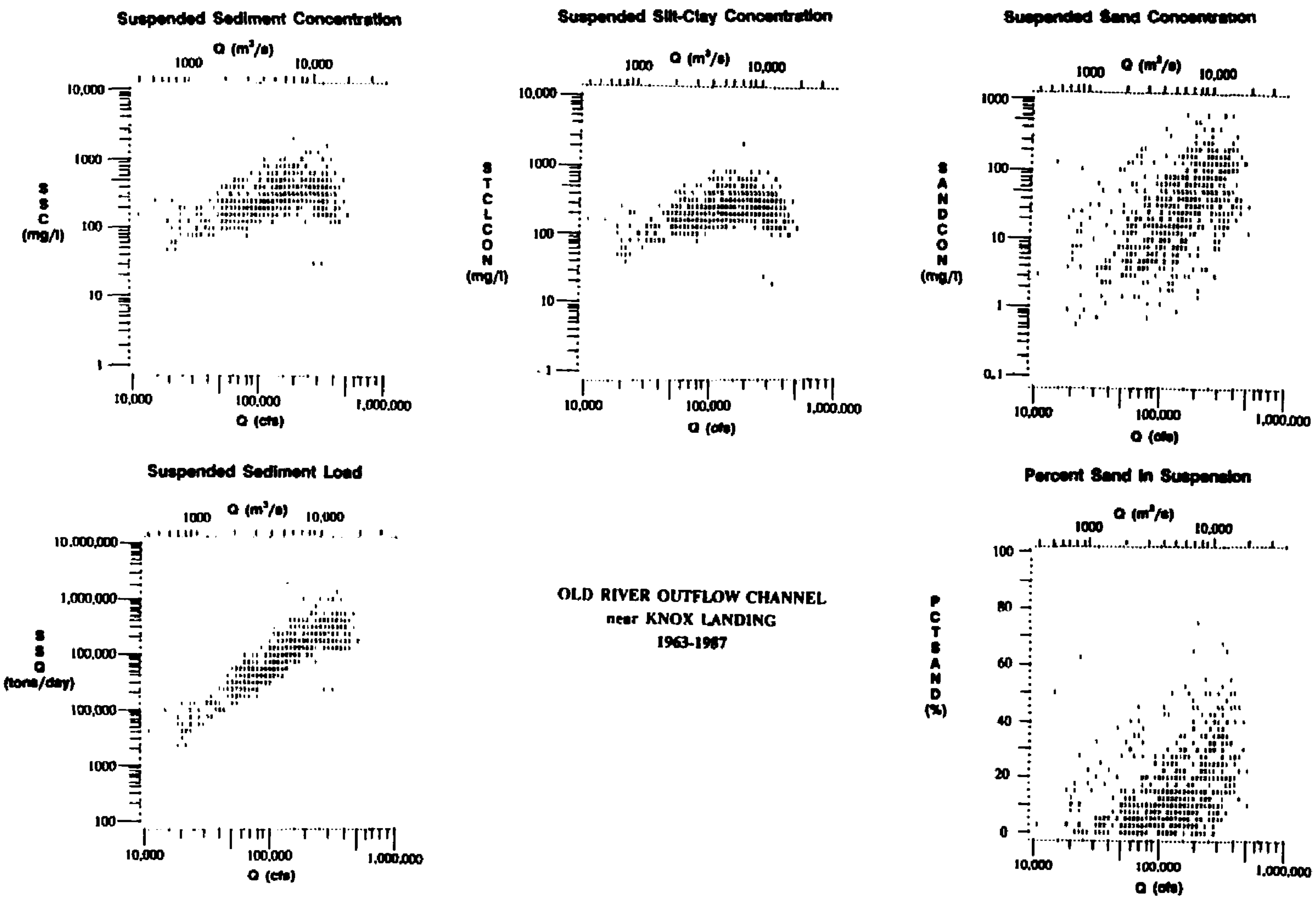


Figure 16. Scattergrams showing relationships between discharge and suspended sediment variables for the Old River Outflow Channel near Knox Landing, 1963-87.

The percentage of sand in suspension on the Old River system generally increases throughout the discharge range (Fig. 16), with scatter being lowest for lower discharges and increasing with increasing discharges. Use of a quadratic log-log function improves the correlation on the Old River Outflow Channel considerably and the graph appears to show a concave-upward curvilinear form.

The quadratic model is significantly different than the linear model for all variables on the Old River Outflow Channel near Knox Landing. Although it is improved with the quadratic model, the explanation of the variance is low. Possibly, the structures introduce additional scatter in discharge-sediment relationships in the Old River Outflow Channel by augmenting turbulence as the water level drops, or by skimming such that coarse sediments in the lower part of the water column in the Mississippi cannot easily enter the diversion.

Empirical relationships between discharge and sediment on the Atchafalaya River at Simmesport

The Atchafalaya, which receives flow and sediment largely from the Mississippi River through the Old River system and also from the Red River, shows some characteristics of both sources (Figs. 17; Table 11). The relationships between discharge and the suspended sediment and silt-clay concentration are nonlinear, such that concentration generally increases sharply with discharge in the lower discharge range, stabilizes for intermediate discharges, and decreases somewhat with higher discharges. Quadratic log-log relationships fit the data better than the linear log-log relationships, and the plots are concave-downward (Table 12). The silt-clay concentration shows a sharper decrease at high discharges and greater peakedness at intermediate discharges than the total suspended sediment concentration, resulting in greater absolute values of the quadratic coefficients for the silt-clay.

Suspended sand concentration on the Atchafalaya River generally shows a more strongly linear relationship and correlation with discharge than suspended silt-clay or total suspended sediment concentration (Fig. 17; Table 11). Sand concentration rises steadily throughout the discharge range, but also shows appreciable scatter. Quadratic log-log functions produce minimal improvements to correlations and the function is concave-downward (Table 11). Compared to the suspended sediment and silt-clay concentration, the absolute values of the quadratic coefficients for sand are lower because of the greater linearity and lesser peakedness in the curve.

The suspended sediment load rises rapidly for low, intermediate, and high discharges, but shows a slight down-turn for the highest discharges. The improvement in correlation with application of a quadratic function is slight, because the down-turn constitutes only a small portion of the graph. As with other locations, the correlations are much greater than for the suspended sediment concentration.

The percentage of sand in suspension, as with the sand concentration, generally increases throughout the discharge range (Fig. 17). Scatter on the Atchafalaya is lowest for lower discharges and increases with increasing discharges. Use of a quadratic log-log function improves the correlation on the Atchafalaya and the plots are concave-upward (Table 11).

The quadratic model is highly significantly different from the linear model for all variables for the Atchafalaya at Simmesport. The explanation of the variance is typically not as good as for the Mississippi except for the sand concentration and percentage sand in suspension. The diversion is one factor that may increase the scatter in discharge-suspended sediment relationships. Input from the Red River, which shows linear relationships, may act to reduce some of the scatter.

Trend is also a source of scatter and is documented in the previous chapter. The mean suspended sediment concentration shows statistically significant declining trends, whilst the mean discharges do not show trends (Figs. 8 and 9; Table 8). The reasons for nonlinearity in the Mississippi hold for the Atchafalaya, in that the silt-clay supply is limited from local sources. The increased peakedness of suspended sediment and silt-clay probably reflects appreciable contributions from the Red River. Such increased contributions are not seen at high discharges because the discharge magnitudes of the Mississippi dwarfs the Red, and because high discharges on the Red River have come in years other than high discharges on the Mississippi, as discussed in the previous chapter.

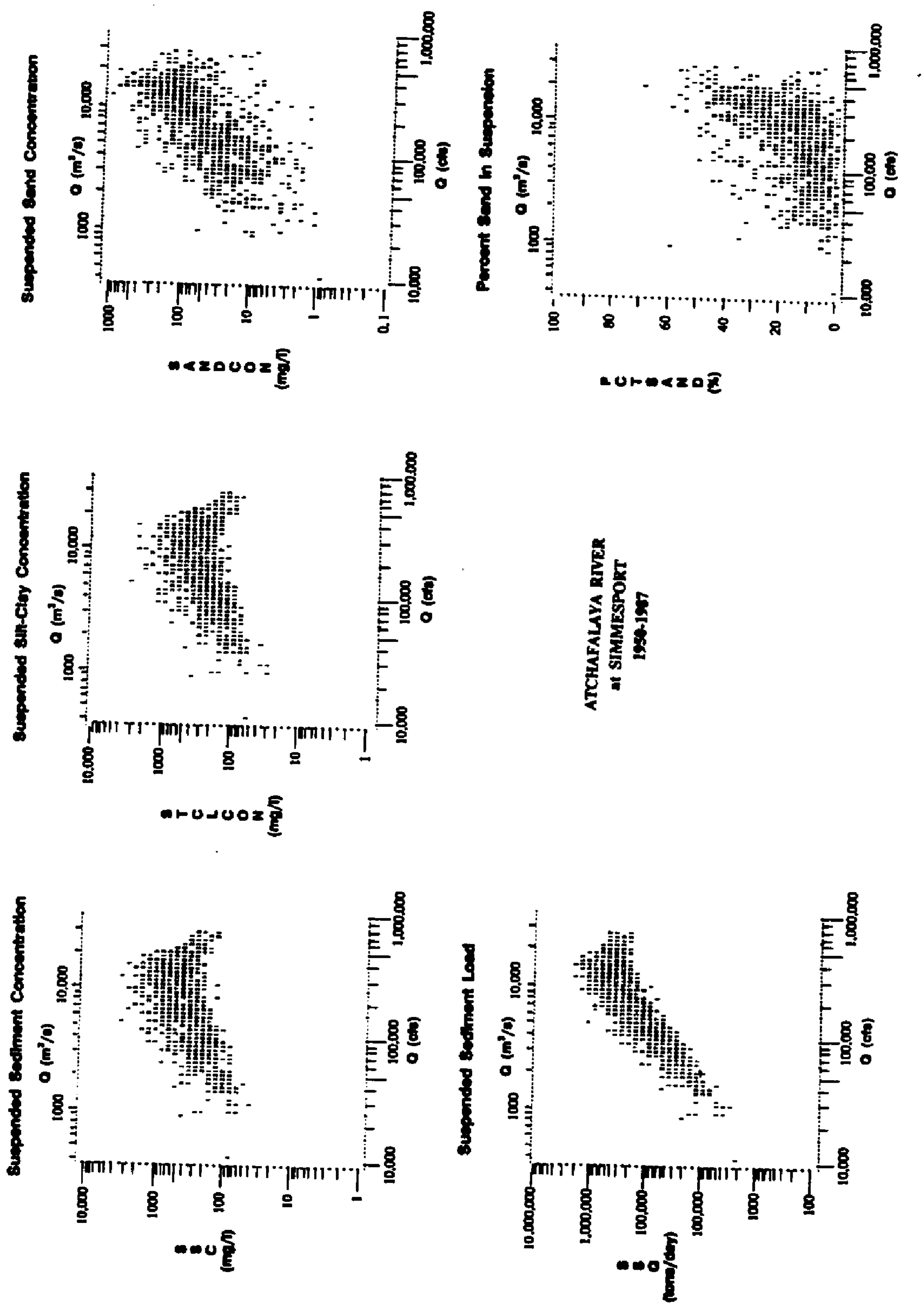


Figure 17. Scattergrams showing relationships between discharge and suspended sediment variables for the Atchafalaya River at Simmesport, 1950-87.

<u>System similarities and differences</u>

The Mississippi River below the diversion, the Old River Outflow Channel, and the Atchafalaya at Simmesport all show nonlinear relationships between discharge and the suspended sediment and silt-clay concentration (Figs. 11, 16 and 17; Table 11). Total and silt-clay concentration generally increase sharply with discharge in the lower discharge range, are fairly uniform for intermediate discharges, and decrease somewhat with higher discharges. Quadratic log-log relationships fit the data better than the linear log-log relationships, and the plots are concave-downward (Table 12). The absolute values of both quadratic coefficients for the Old River Outflow Channel and Atchafalaya are smaller than the Mississippi. From an algebraic viewpoint, this is because the data extend over a larger range of discharge log-cycles. The absolute value of the quadratic coefficient of silt-clay concentration is generally greater than that for the total suspended sediment concentration because the silt-clay generally decreases more sharply at high discharges. The nonlinearity of suspended silt-clay concentration appears to be related to its limited availability and its transport through the system by the flushing process. Even on the Atchafalaya, which receives substantial contribution from the Red, these relationships are nonlinear because at the highest discharges a comparatively large proportion of the flow is from the Mississippi. The total suspended sediment concentration follows a nonlinear form because the silt-clay is the dominant component.

Suspended sand concentration generally shows a more strongly linear relationship and correlation with discharge at these three locations than suspended silt-clay or total suspended sediment concentration (Figs. 11, 15, and 17; Table 11). The plots and functions for the Mississippi River initially show rapidly rising concentrations with increasing discharges followed by no or low increases for highest discharges. The Atchafalaya and Old Rivers show steadily rising concentrations throughout the discharge range. Quadratic log-log functions improve correlations for the Mississippi, but produce minimal changes at the other locations (Table 11). The slight nonlinearity in the sand component may be due to greater removal in the early part of the flood event although the causes for this nonlinearity are still not well understood.

The suspended sediment load at these three locations rises rapidly for low discharges. On the Mississippi, it increases more rapidly with increasing discharges in the intermediate discharge range and stabilizes at the highest discharges. On the Atchafalaya and Old rivers suspended load stabilizes or shows a down-turn for the highest discharges. Correlations improve with a quadratic log-log function, particularly on the Mississippi which shows a curvilinear form; the improvement is not appreciable at the other locations because the down-turn constitutes only a small portion of the graph. The regressions with load, as compared to concentrations, change the correlations and generally introduce appreciable biases.

As with the sand concentration, the percentage of sand in suspension generally increases throughout the discharge range (Figs. 11, 16, and 17). The Mississippi shows the greatest scatter, with large ranges of percentages throughout the discharge range. Scatter on the Atchafalaya and Old rivers increases with increasing discharges. Use of a quadratic log-log function improves the correlation on the Atchafalaya and Old River Outflow Channel more so than the Mississippi.

The explanation of the variance for both the linear and quadratic models on the Mississippi at Belle Chasse is much better than upstream below the diversion. The Belle Chasse plots show reduced scatter probably because of the shorter period of record. The plots may also differ because of changes in hydraulics from upstream to downstream, and the increased availability of silt and clay on the bed downstream. Hydraulic changes include the lower velocities at low discharges downstream associated with the deeper channel and larger cross-sectional area. Differences in velocity and cross sectional area become smaller with increased discharges as the depth difference decreases and gradient across the reach increases with increasing discharges. Extremely low velocities allow for settling of silt and clay on the bed, which may explain some of the grain size differences between Belle Chasse and upstream. While the silt-clay at the Mississippi below the diversion is acquired mostly from upstream locations, an additional source of silt-clay at Belle Chasse is the bed, such that resuspension is an important mechanism for sediment movement.

The Red River is quite unlike the Mississippi-fed locations in that the relationships between discharge and the sediment concentration parameters are all highly linear. Suspended sediment and silt-clay concentrations on the Red River at Alexandria also show the least scatter, and the highest maximum concentrations of the rivers and sampling locations in the study area. Probable reasons for the greater linearity and better explanation include the shorter period of record, which reduces the effects of trend, and the abundance of silt and clay from the basin and/or the channel perimeter, such that supply does not decline at high discharges. Some explanations for the increased silt-clay availability include hydraulics, climate, geology, and human-induced changes.

The quadratic vs. linear model differences are highly significant for all variables on the Mississippi below the diversion, the Old River Outflow Channel, and the Atchafalaya at Simmesport (Table 12). At Belle Chasse, the quadratic models also show higher correlations than linear models and are significant or highly significant for all parameters. The model differences are not significant for the Red River at Alexandria, in which discharge-suspended sediment relationships are fairly well explained by the linear models (Table 12).

SYSTEM BEHAVIOR INTERPRETED FROM HIGH TO LOW DISCHARGE YEARS: HYSTERESIS AND OTHER PHENOMENA

Some of the causes of the large scatter in discharge-suspended sediment relationships can be inferred if temporal variations in these relationships are analyzed. Although there are various timescales at which discharge-suspended sediment relationships can be interpreted, this study identifies some of the major relationships that occur within the annual cycle. Because the annual cycle on the Mississippi and Atchafalaya rivers typically shows seasonality in discharge (e.g., Jordan, 1965; Roberts et al., 1980), the water year is an important frame of reference for cyclic behavior. Additional types of periodic phenomena between discharge or velocity and suspended sediment may be apparent on much larger and much smaller timescales that are not apparent in the annual data.

The conceptual diagram

On an annual basis, discharge magnitude of the major flood is one of the principal factors that influences suspended sediment responses. It is hypothesized that discharge magnitude influences the timing of suspended sediment such that high discharge years show increased hysteresis compared to low discharge years, because of supply limitations and bankfull flows. A conceptual diagram is presented that is derived from the empirical relationships on the Mississippi-fed rivers and serves as a basis for discussion (Fig. 18). This conceptual diagram is inferred from the empirical plots in the previous chapter and previous literature and is based on the circumstance that as the maximum annual discharge increases, the range of discharge increases. In low discharge years, the discharge range may not extend past the central portion of the scatter plot, and thus concentrations do not show a decline. In intermediate discharge years, discharges extend beyond the midpoint of the scatter plot and concentrations show some decline at the higher discharges in these years. In high discharge years, discharge range extends across the scatter plot and concentration show a decline for a greater proportion of discharge conditions. Although not depicted, it is hypothesized that this conceptual diagram might not be valid for the Atchafalaya in years when the contribution from the Red River is significant, and particularly if it exceeds the contribution of the Mississippi through Old River Outflow Channel.

Commonly, concentration increases with increasing discharges, and similarly would decrease with decreasing discharges given that the empirical relationships are often linear and that the bed material load and in some cases the wash load are directly related to changes in velocity. However, as previous studies have suggested, hysteresis effects and other phenomena occur in a substantial number of rivers, such that concentration declines when the discharge increases or rises when the discharge falls. Four types of possible relationships are shown on the conceptual time series and bivariate plots (Fig. 18) and include Type QRCR where both discharge and concentrations are rising, Type QFCF where both discharges and concentrations are falling, Type QRCF with rising discharge and falling concentrations, and Type QFCR with falling discharge and rising concentration.

In addition to characterizing the relative conditions of discharge-suspended sediment relationships, the peaks and troughs themselves can also be related to the fluctuations of the hydrograph. At least four types of sediment peaks can be discerned on the time series graphs: 1) Major flood sediment peaks; 2) Secondary flood sediment peaks; 3) Stationary discharge sediment peaks; and 4) Falling discharge sediment peaks. The term peak is herein used to describe a sediment apex, whereas the term crest is used to describe a discharge apex. Suspended sediment troughs include those in phase with discharge troughs, those concurrent with discharge crests, those occurring on the rising limb, and/or those occurring on the falling limb. Sediment peaks represent increased sediment supply from increasing discharges, tributary contributions, bank failures, resuspension, or flushing, while sediment troughs most likely represent a decline in supply.

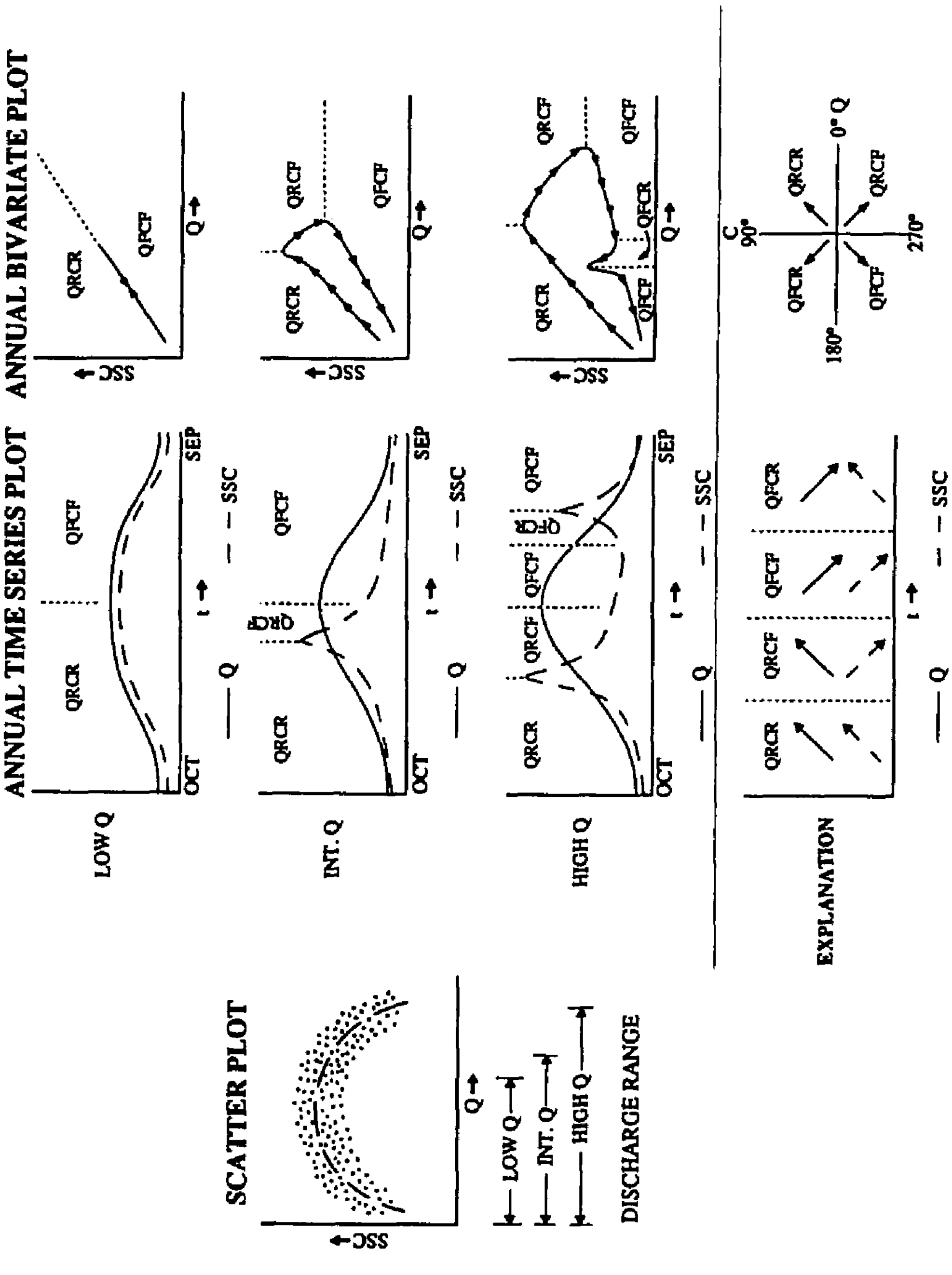


Figure 18. Preliminary conceptual diagram of discharge-suspended sediment relationships shown on annual time series and bivariate plots for the Mississippi River during low, intermediate, and high discharge years with a single major flood crest. Actual hydrologic and sediment events may be more complex than depicted.

A series of annual discharge and suspended sediment graphs is presented for the Mississippi-Atchafalaya system (Figs. 19 to 28) in order of decreasing magnitude. These include high discharge years, with return periods near or greater than 20 years, and low discharge years with return periods near or less than 1.05 years. Years intermediate to these have return periods of 5, 2, and 1.25 years. Time series graphs for years which are not discussed are presented in Appendix A. There are several factors that are not investigated in detail in this study, but are recognized as possible causes of the scatter in discharge-suspended sediment relationships over a long time frame. These include the rate of discharge increase or decrease and other aspects of hydrograph form, natural and human-induced local and regional changes in sediment supply, and the antecedent conditions such as a succession of flood or low water years.

Discharge-suspended sediment relationships in water year 1973

The 1973 flood has the largest maximum discharge during the study period with a return period close to 50 years (Tables 9 and 10). In many locations in the alluvial valley it is the second largest event of the century. Despite this, the major flood sediment concentration peak on the Mississippi is quite unimpressive compared to other peaks in the same year. There is a slight increase in concentration of less than 100 mg/l on the rising limb about 70 days before discharge crest and an associated short-lived drop in percentage sand in suspension (Fig. 19). Sand content increases immediately following the silt-clay peak. Secondary flood sediment peaks, of which there are three in the fall, show greater amplitude in concentration than the major flood peak, and occur about ten days before their corresponding crests. Of the secondary sediment peaks, the first shows increased sand percentages, and possibly reflects resuspension of material from the channel perimeter with the initial flow increase after low water. The remaining two secondary peaks show pronounced drops in sand percentages, indicating that the sediment peak is principally composed of silt and clay. There are no significant peaks during stationary or falling discharges. Overall, percentage sand in suspension in 1973 is high.

The longest and lowest concentration trough occurs during the major flood crest and falling limb, and results in extreme seasonality with concentrations being greatest during winter in the early part of the water year (Fig. 19). Concentrations during low flows early and late in the water year are greater than during the flood crest and on the falling limb. Sand percentages decline during the flood crest and falling limb, possibly because the velocities associated with the discharge crest are no longer increasing. However, percentages of sand in suspension are much greater during the discharge crest than they are at low flows. The first concentration trough between the secondary peaks is coincident with a discharge trough, whereas the remaining two troughs are coincident with discharge crests.

The Red River shows multiple flow events, with the mean discharge ranking sixth, and the maximum flood with a return period between 2 and 5 years (Tables 9 and 10). Unlike the Mississippi, sediment peaks and flood crests are concurrent, as are the sediment troughs with the discharge troughs (Fig. 19). Because of the comparatively large quantities of flow diverted through Old River Outflow Channel, numerous sediment crests that are manifest on the Red River are not apparent on the Atchafalaya. When discharges on the Mississippi are high, but those on the Red are not exceptional, the Red has little influence on the Atchafalaya.

The major flood sediment peak on the Old and Atchafalaya rivers is much more pronounced than the Mississippi, and also occurs about 70 days before the peak flood (Fig. 19). It is the largest peak on the Atchafalaya and shares this position on the Old River Outflow Channel. The large peak on Old River Outflow Channel indicates probable resuspension by the rising flows. The even greater increase on the Atchafalaya indicates appreciable sediment input from the Red River. Of the secondary peaks that occur on the Mississippi, the Old River Outflow Channel shows the first two of the three, with the first being tied for largest. The first of the three secondary peaks is present on the Atchafalaya but the others are not, in part because of sampling strategy. As with the Mississippi, secondary peaks in water year 1973 typically occur on the rising limb and show small leads or coincide with discharge crests.

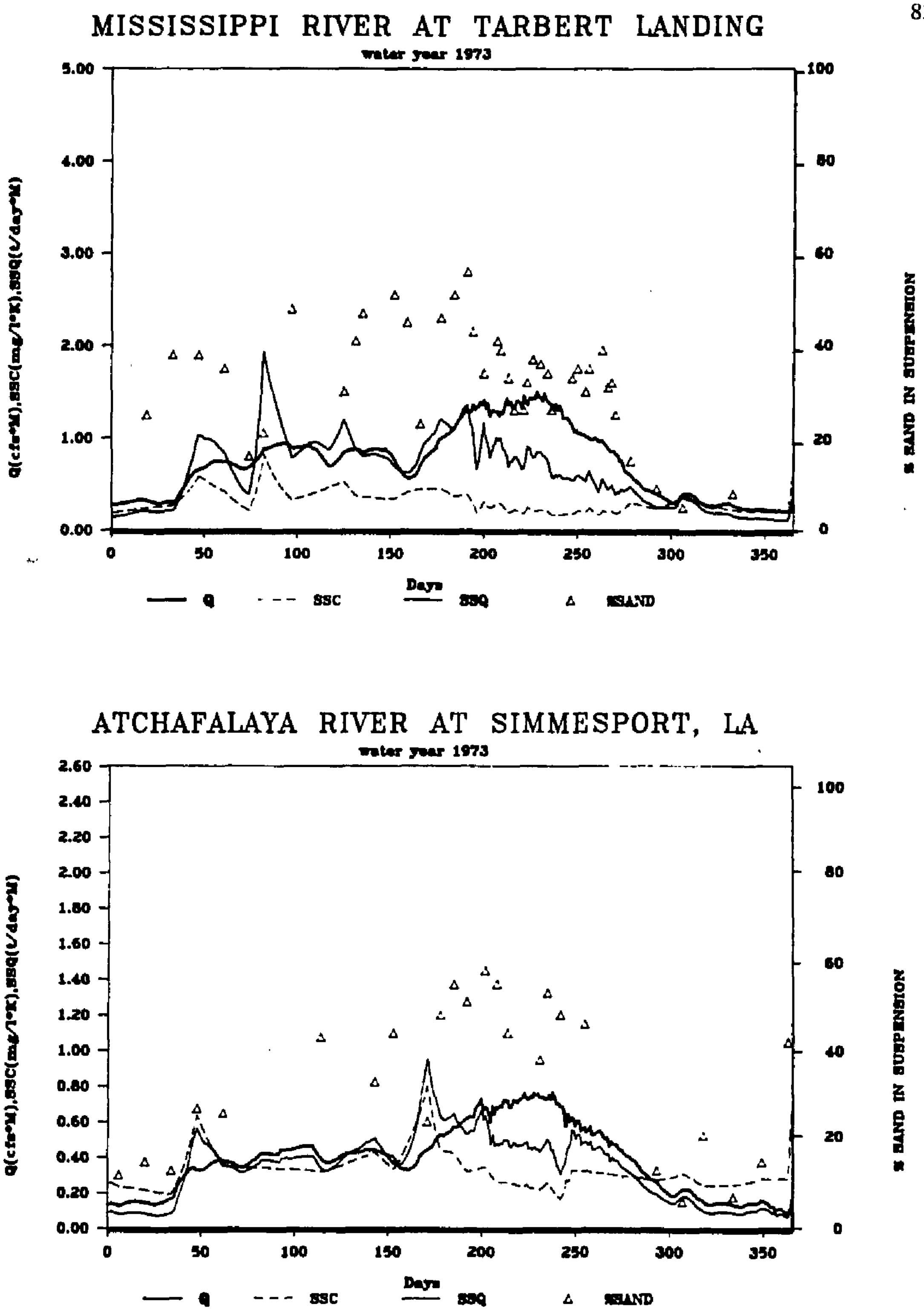
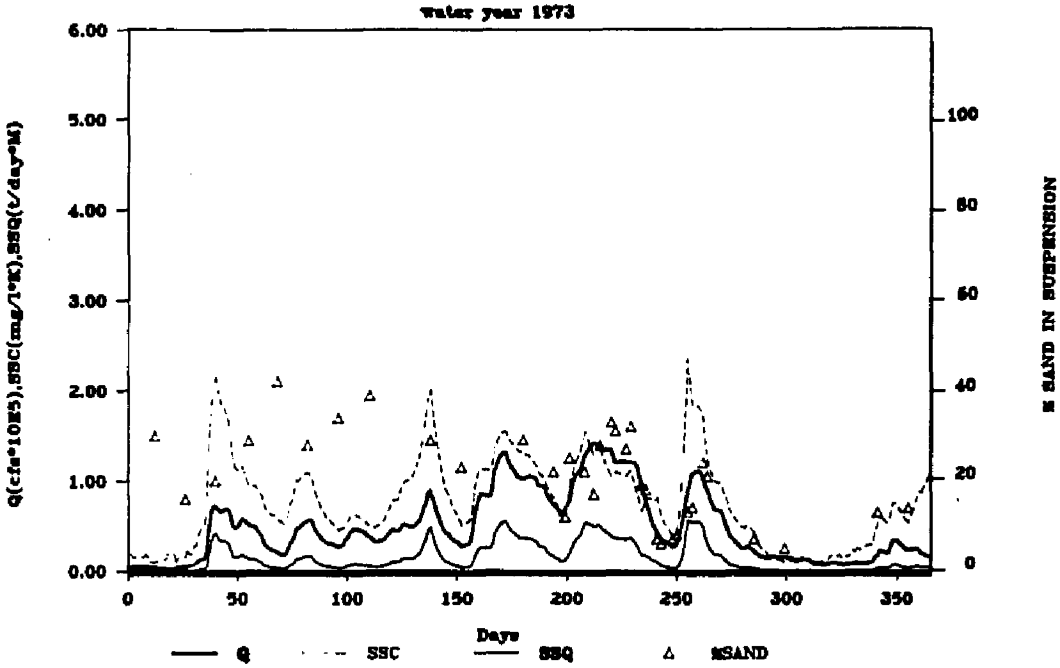


Figure 19. Discharge-suspended sediment relationships for water year 1973 on the Mississippi-Atchafalaya river system.



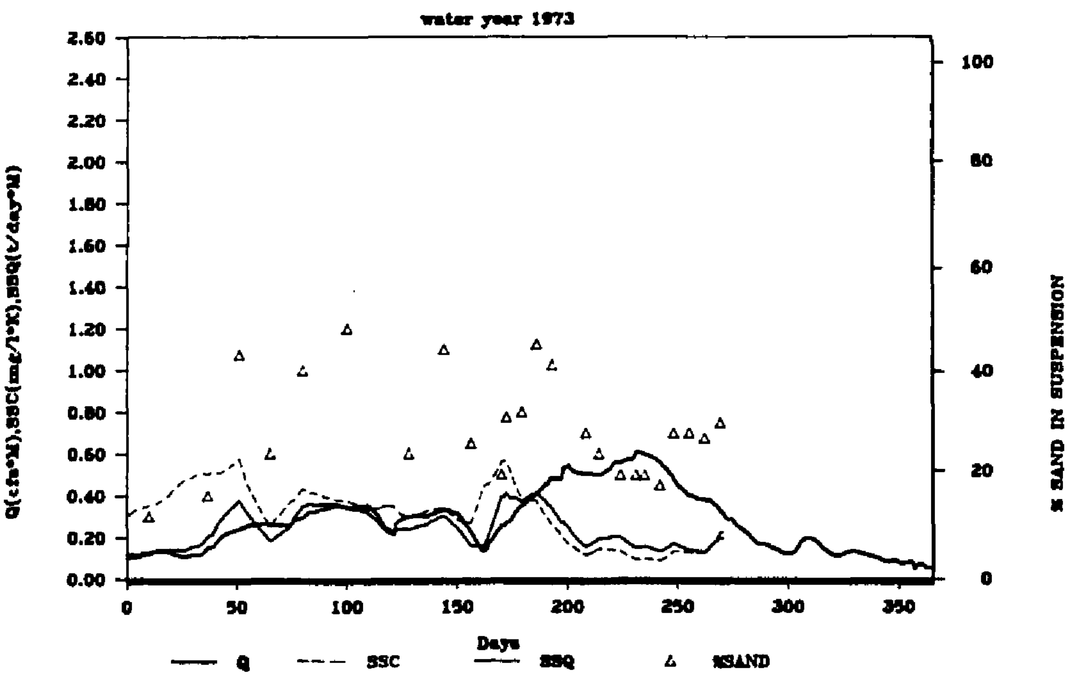


Figure 19 (cont.). Discharge-suspended sediment relationships for water year 1973 on the Mississippi-Atchafalaya river system.

Discharge-suspended sediment relationships in water year 1983

The 1983 flood has the second largest maximum discharge on the Mississippi below the diversion during the study period, and a return period between 20 and 50 years (Tables 9 and 10). Water year 1983 has two major flood crests, one in late fall-early winter and one in spring. The 1983 flood on the Mississippi dwarfs the comparatively smaller floods on the Red River that shows mean discharges ranking eleventh, and the maximum flood having a return period between 2 and 5 years (Tables 9 and 10). Sediment peaks occur on the rising limb and lead the discharge crests by about 40 days for the fall-winter event at all three Mississippi-fed locations, and by about 60 days for the second and larger spring event (Fig. 20). The first and smaller of the two sediment peaks shows increased sand percentages as flows initially increase in fall, and the second shows reduced sand percentages, indicating that the sediment peak is principally composed of silt and clay. There are no secondary peaks in water year 1983, although a minor peak occurs during stationary discharges on the falling limb of the major flood.

The troughs in concentration in water year 1983 slightly precede or coincide with flood crests on the Mississippi (Fig. 20). These result in extreme seasonality with concentrations being greatest during winter in the early half of the water year. Concentrations are greater during low flows than during the larger of the two flood crests. Sand percentages are lower during the first crest and higher during the second crest than flanking parts of the hydrograph.

The timing of sediment peaks on the Old River Outflow Channel in water year 1983 is essentially the same as the Mississippi, although the magnitudes of the peaks are generally smaller. The first peak on the Mississippi is evident on both the Old and Atchafalaya rivers. The Atchafalaya peak is larger than the others, probably due to sediment input from the Red River, although sediment data are not available to support this inference (Fig. 20). A second sediment peak follows the first discharge crest during stationary flows, again, probably related to influx from the Red River. The larger spring flood crest is manifest on the Old River, but is barely evident on the Atchafalaya, implying it may be diluted from the Red River basin. In addition, some minor peaks occur during the summer, one contributed from the Mississippi and the other perhaps due to Red River contributions.

<u>Discharge-suspended sediment relationships in water year 1950</u>

The third largest maximum discharge on the Mississippi during the study period is in 1950, with one major flood crest in winter and a return period between 20 and 50 years (Tables 9 and 10). The absolute magnitude of the maximum discharge is much larger than the Red River, which shows fairly high flows with a return period of more than 5 years and the third highest mean (Tables 9 and 10). The major flood suspended sediment peak on the Mississippi occurs on the rapidly rising limb of the hydrograph about 40 days before the discharge crest (Fig. 21). By the time the flood crest passes, concentrations are greatly reduced, although the troughs are much higher during the flood than at low flow at the beginning of the water year. Concentrations are still large during the latter part of water year, because of the increased suspended sediment availability in the Mississippi basin at this time compared to more recent years.

Also of note is an unexplained peak, not associated with a significant increase in discharge, in mid-summer (Fig. 21). It occurs about 170 days after the major flood crest when discharge is low and falling. Although only the fall data is available for the Atchafalaya, a similar peak is noted at the same time of year. Such sediment peaks reflect a great variety of possible causes, e.g., contributions from sediment-laden tributaries, greater runoff and erosion in late spring and summer, bank failures, and human activities. Percentage sand in suspension in water year 1950 corresponds with discharge patterns, and did not seem to change during passage of the sediment peaks.

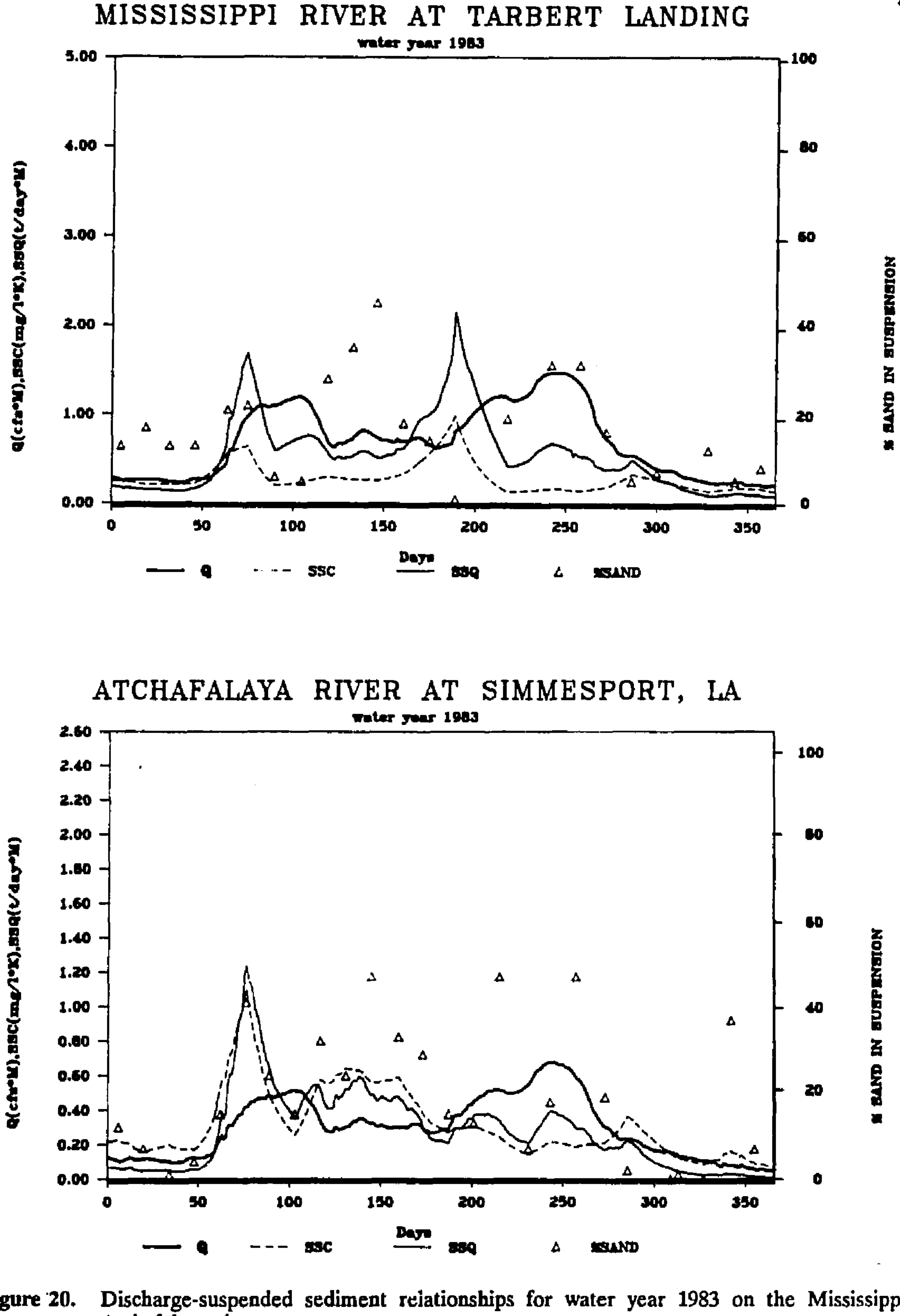


Figure 20. Discharge-suspended sediment relationships for water year 1983 on the Mississippi-Atchafalaya river system.

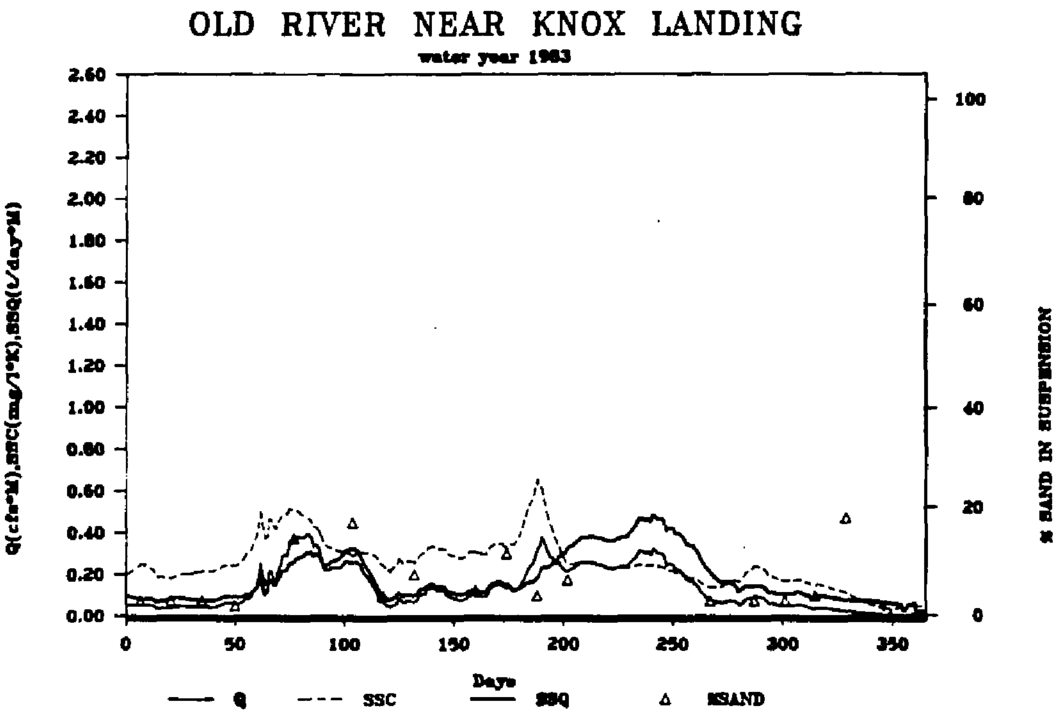


Figure 20 (cont.). Discharge-suspended sediment relationships for water year 1983 on the Mississippi-Atchafalaya river system.

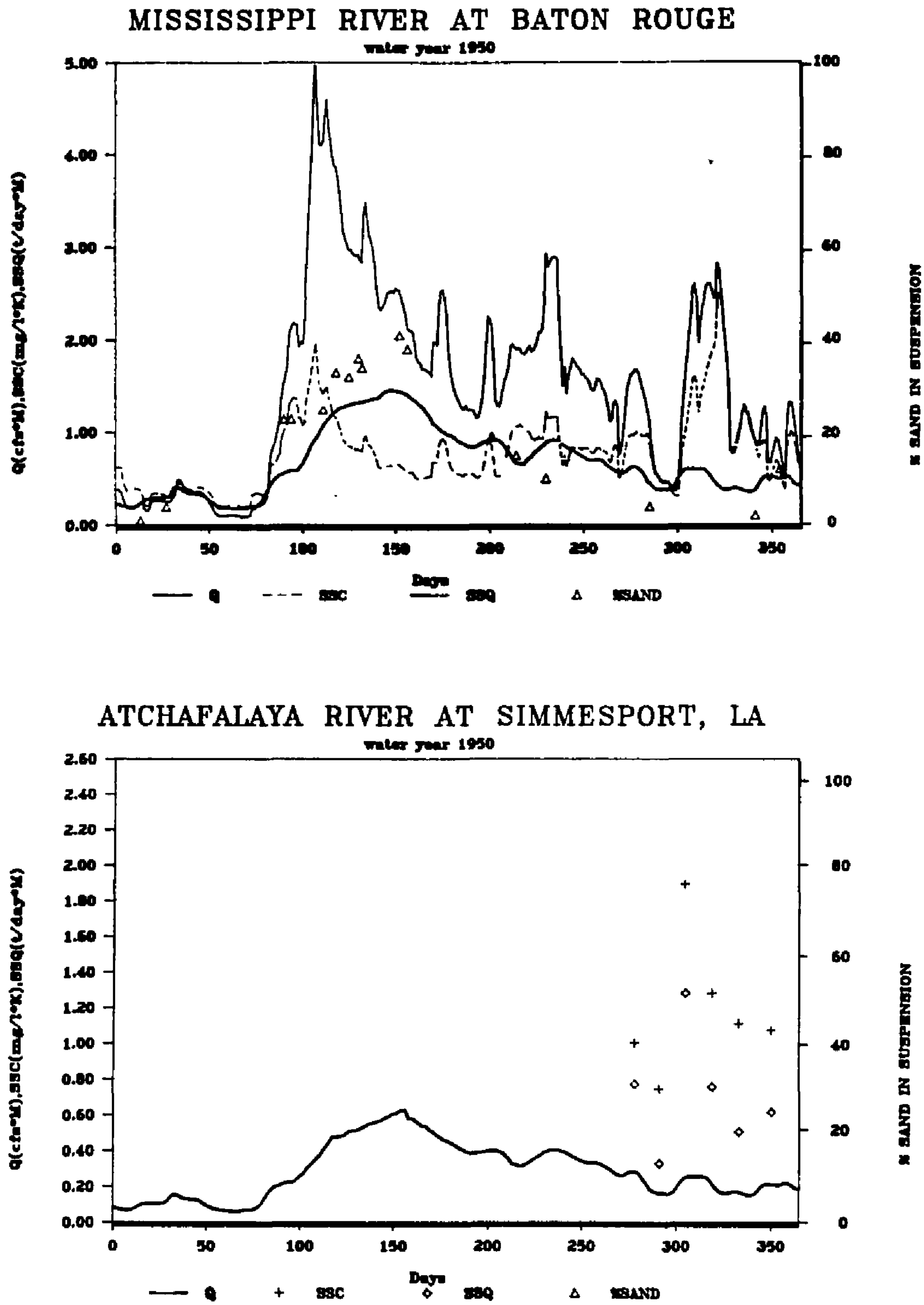


Figure 21. Discharge-suspended sediment relationships for water year 1950 on the Mississippi-Atchafalaya river system.

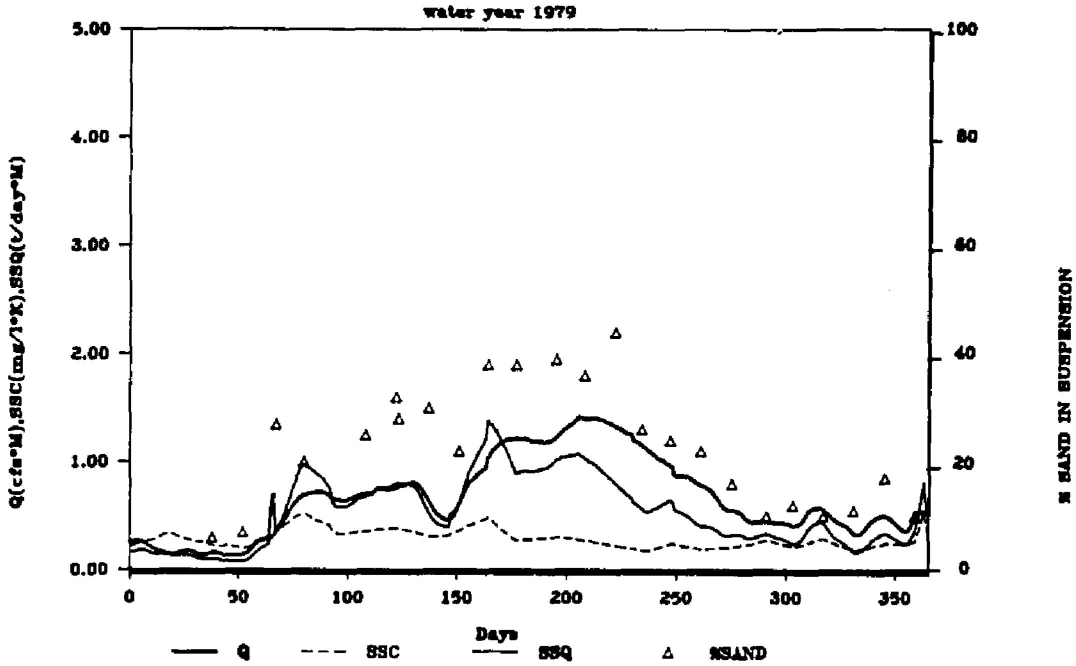
Discharge-suspended sediment relationships in water year 1979

Maximum discharge on the Mississippi in water year 1979 was the fourth largest of the study period and showed a return period just over 20 years (Tables 9 and 10). The suspended sediment peak associated with the major flood occurs on the early part of the rising limb about 10 days before an initial discharge plateau and about 40 days before the ultimate flood crest in early spring (Fig. 22).

Of the secondary floods, the first shows a peak of equal or greater magnitude to the major flood crest with the peak preceding the discharge crest by 5 days (Fig. 22). Some other secondary peaks of short duration and magnitude occur in late summer. Troughs of suspended sediment concentration are not pronounced, and concentrations are generally lower on the falling limb after the flood crest and than during low discharges. Percentage sand in suspension in water year 1979 corresponds with discharge patterns. The secondary sediment peak shows decreased sand percentages, whereas the one associated with the flood shows no change. There are no significant peaks during stationary or falling discharges.

The Red River shows the highest mean flows of the study period although the return period of the annual flood is just greater than 2 years (Tables 9 and 10). Water year 1979 shows multiple flow events, with sediment peaks and flood crests being approximately concurrent, as are the sediment troughs with the discharge troughs (Fig. 22). The large mean discharge of the Red River results in a distinct signature on the Atchafalaya, in which there are numerous crests during fairly stationary or falling discharges. Although some of the sediment crests on the Red River are not manifest on the Atchafalaya, overall, the Red River has a pronounced influence on discharge-suspended sediment relationships. Concentrations on the Red are generally much greater than the Mississippi, but sediment peaks are not highly discernible on the Atchafalaya unless the sediment load, rather than concentration, contributions are large. However, this year shows that the influence of the Red on the Atchafalaya is notable when the Red is high even if the Mississippi is high also.

MISSISSIPPI RIVER AT TARBERT LANDING



ATCHAFALAYA RIVER AT SIMMESPORT, LA

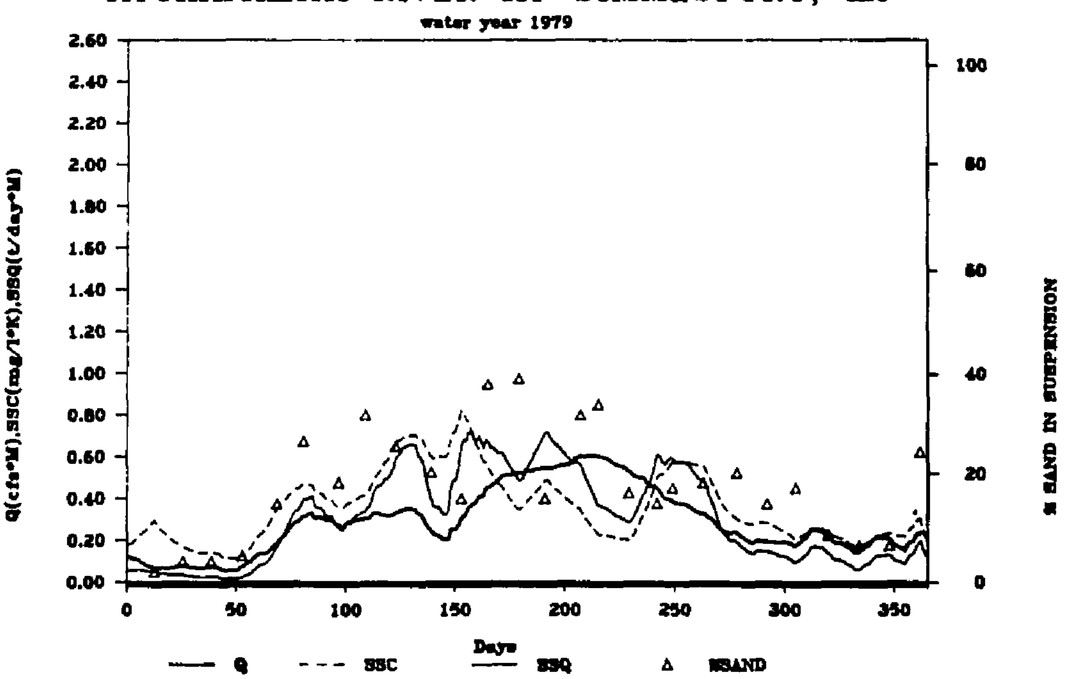
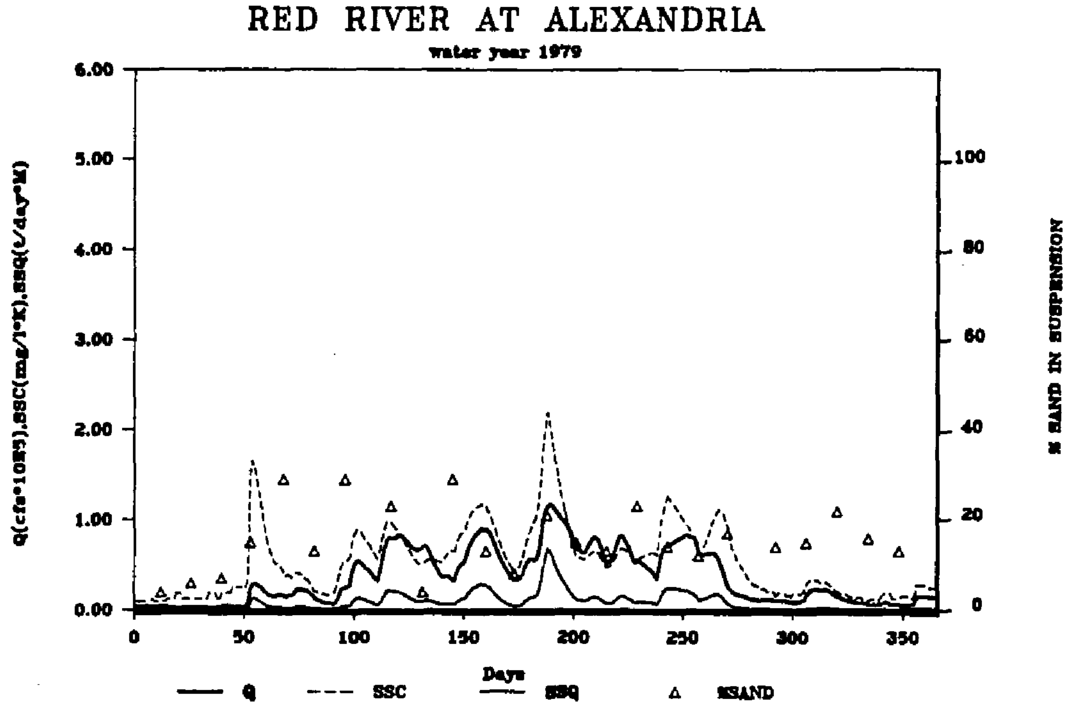


Figure 22. Discharge-suspended sediment relationships for water year 1979 on the Mississippi-Atchafalaya river system.



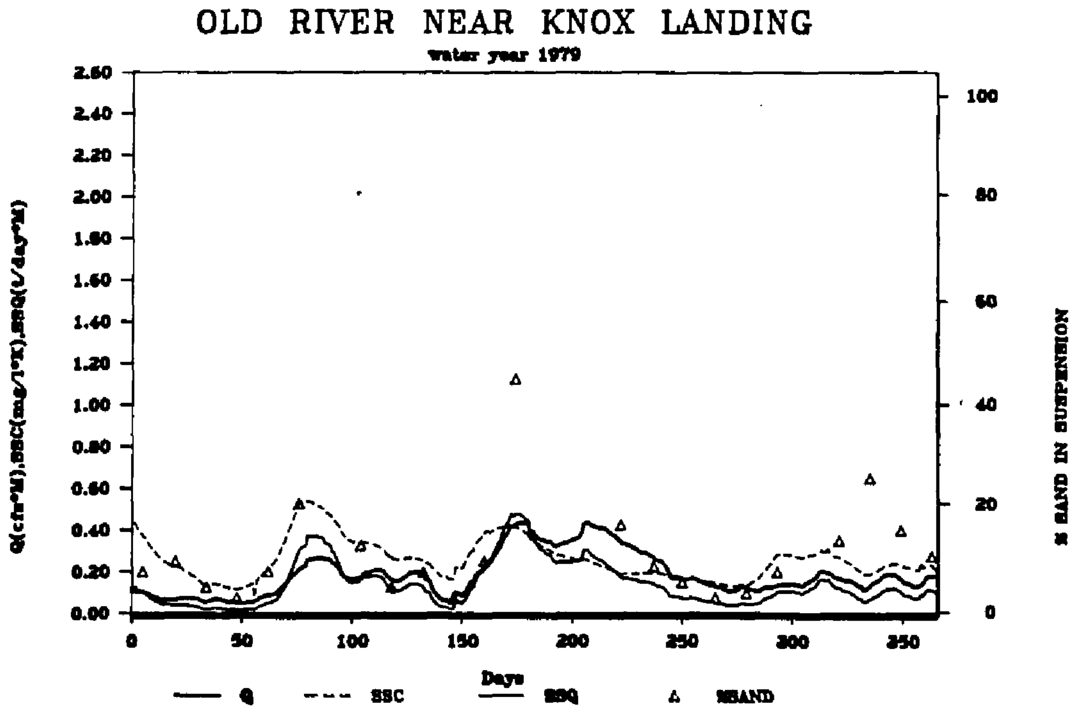


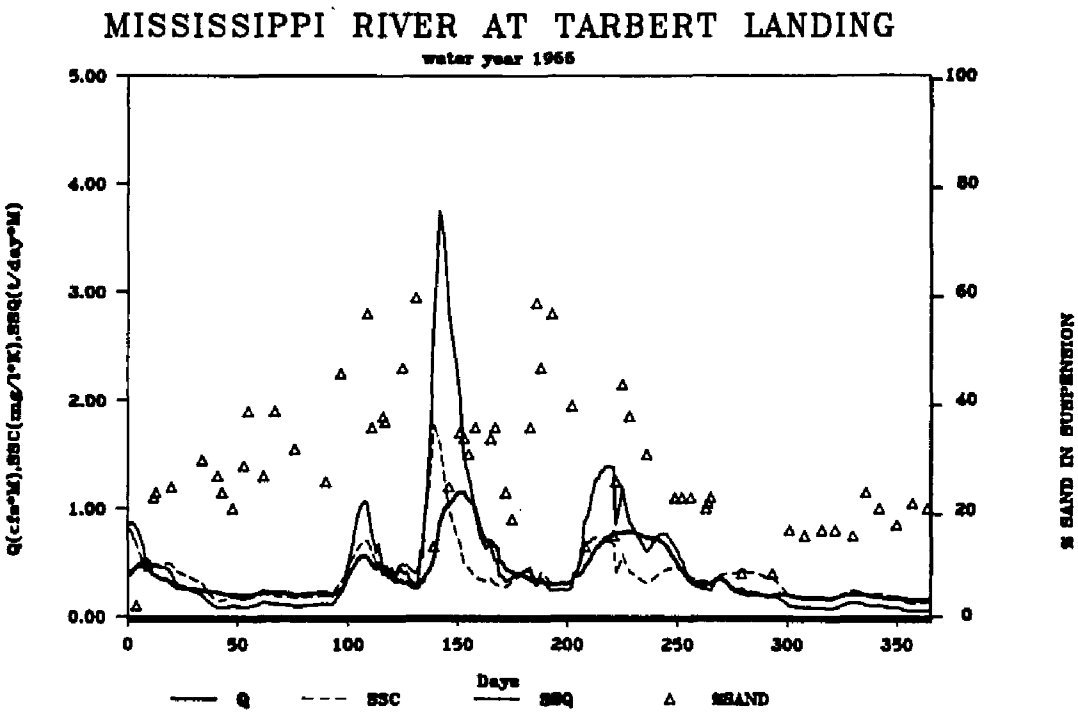
Figure 22 (cont.). Discharge-suspended sediment relationships for water year 1979 on the Mississippi-Atchafalaya river system.

The Old River Outflow Channel shows similar temporal variations in suspended sediment as the Mississippi, although there appears to be greater activity in the fall and summer (Fig. 22). The Atchafalaya shows a few additional peaks not on the Mississippi and Old River Outflow Channel, most which are coincident with sediment crests on the Red River, and some short-lived peaks which occur during falling discharges.

Discharge-suspended sediment relationships in water year 1966

Compared to the previous examples, the annual flood on the Mississippi in water year 1966 is much smaller with a return period of about 5 years (Tables 9 and 10). The major and secondary floods show fairly sharp rises and falls such that the Mississippi River shows an episodic flood pattern as manifest during most years on the Red River, and has sediment peaks that correspond well with discharge crests (Fig. 23). However, unlike the Red, hysteresis effects are apparent with sediment crests occurring on the rising limb up to 20 days before the associated flood crests, indicating that there are some fundamental differences in the availability of material for transport between both rivers. The sediment peaks show increased silt-clay percentages, and are followed by an increase in sand percentages. If climate and vegetation are important reasons for differences in the sediment availability between these basins, then a hypothesis worthy of further inquiry is to determine if hysteresis effects are less pronounced in semiarid climates because of the increased sediment availability. Similarly, revetted channels and bedrock channels might show greater hysteresis effects.

During secondary floods, hysteresis effects are not apparent in water year 1966. The troughs coincide with the falling limb following the major floods, and coincide with discharge troughs otherwise but are lowest at low discharges (Fig. 23). Percentage sand shows a strong seasonal pattern, but decreases during the passage of the first secondary flood crest in fall and the two larger flood crests in late winter and in mid-spring. Minor peaks occur during the falling limbs of the major floods and during the fairly stationary parts of the hydrograph.



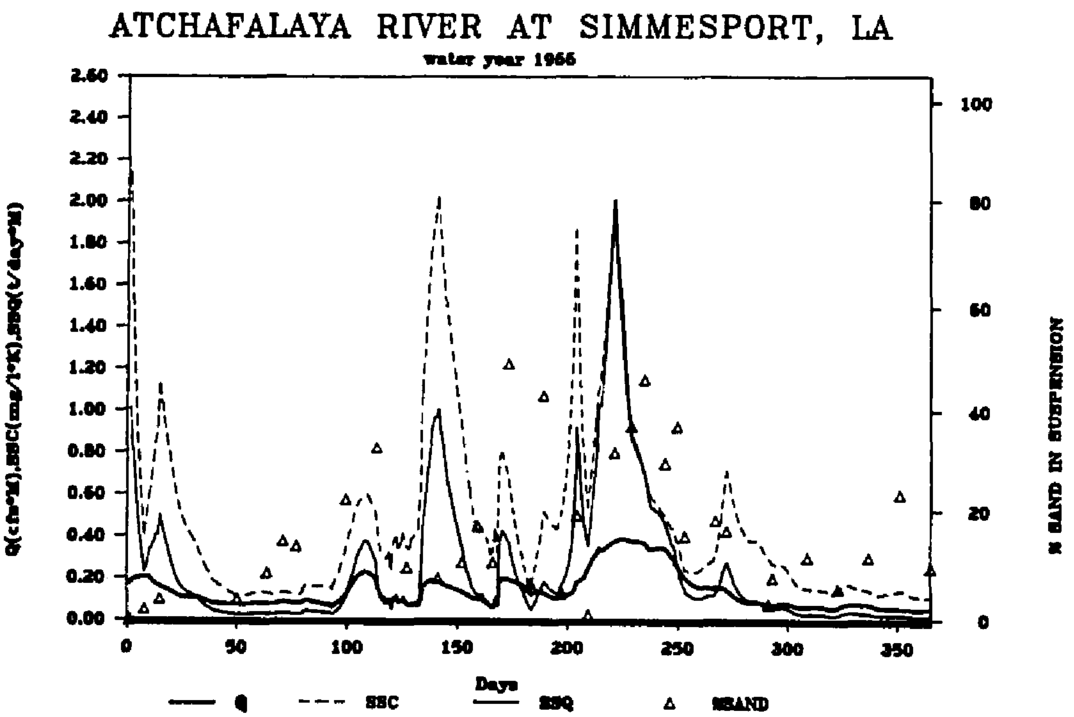
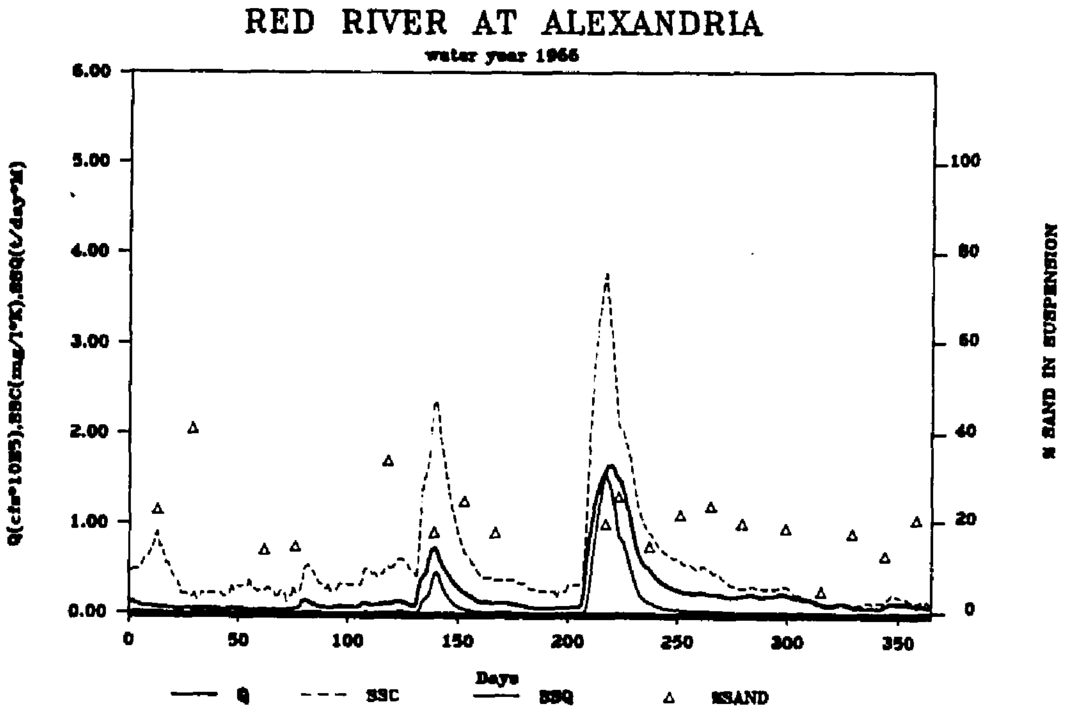


Figure 23. Discharge-suspended sediment relationships for water year 1966 on the Mississippi-Atchafalaya river system.



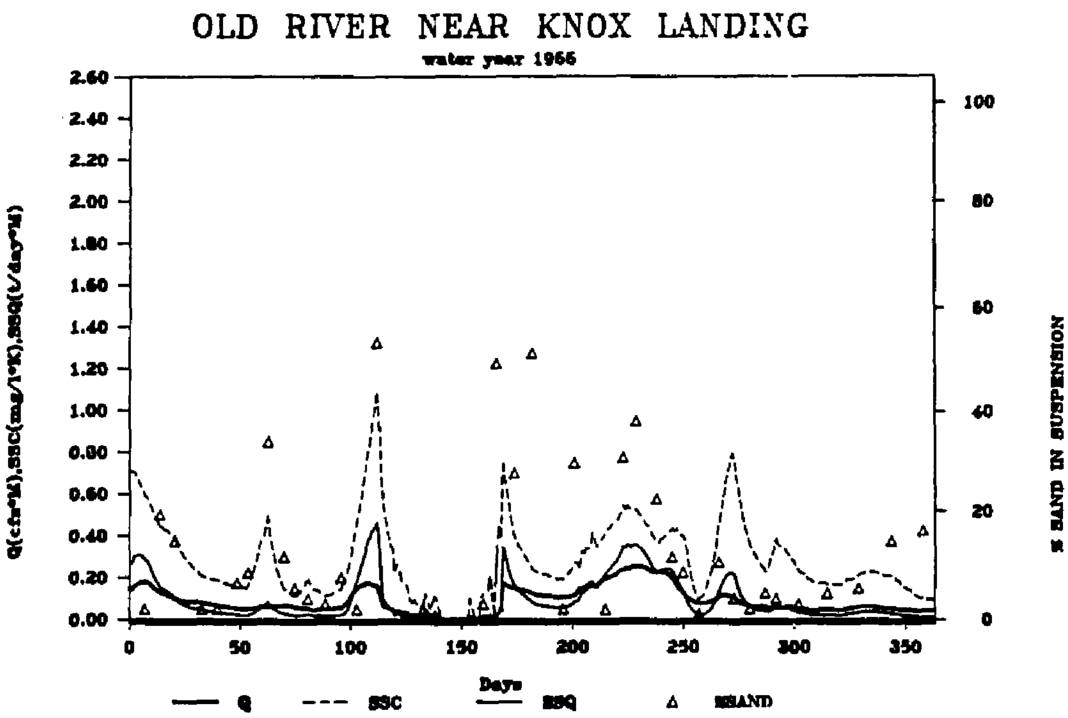


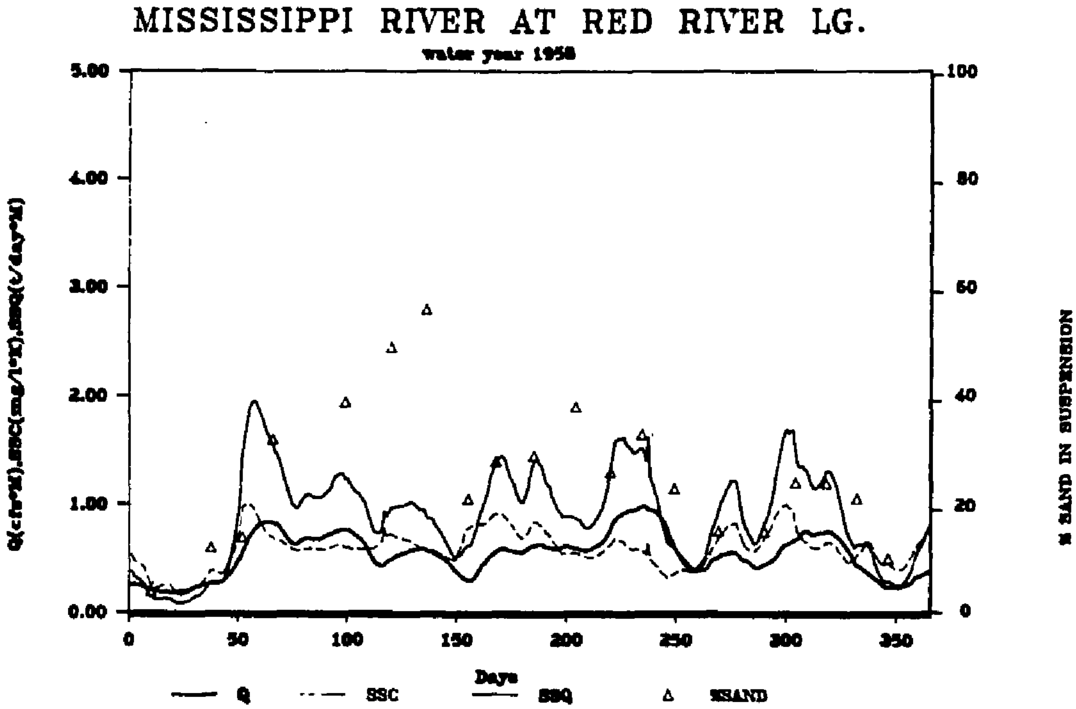
Figure 23 (cont.). Discharge-suspended sediment relationships for water year 1966 on the Mississippi-Atchafalaya river system.

The Red River shows the largest discharge in water year 1966 for the part of the study period when sediment data are available and has a return period of 10 years (Tables 9 and 10), although mean discharges are less than average. As usual, the Red River shows coincident timing of discharge crests and sediment peaks with the exception of the increased concentrations in early fall during low discharges (Fig. 23). The influence of the Red when discharge is high, but low in the Mississippi, is quite pronounced on discharge-sediment relationships in the Atchafalaya.

The Old and Atchafalaya rivers show quite different patterns from the Mississippi, partly because during the largest event on the Mississippi in mid-late winter, the Control Structures were closed and flows were not released (Fig. 23). The Atchafalaya, however, received flow from the Red River and shows a major sediment peak but only a minor discharge crest. The major flood occurs in spring outside of the Mississippi and the corresponding sediment peak coincides with the flood. Secondary sediment peaks in the Old and Atchafalaya rivers show short-lived repeated fluctuations rather numerous to mention, possibly related to excessive sediment availability following construction of the Old River Control Project, Outflow Channel and associated revetments in addition to the larger-than-average contributions from the Red River. Some short-lived sediment peaks also occur on the Old and Atchafalaya rivers when discharges are stationary or falling, particularly early and late in water year, that may reflect phenomena such as tributary contributions or bank failures.

Discharge-suspended sediment relationships in water year 1958

Of even smaller magnitude, the annual flood on the Mississippi River in water year 1958 has a return period of about 2 years (Tables 9 and 10). About half the events in the study period are of greater magnitude and half are not. The hydrograph is quite chaotic, showing several minor oscillations that occur on the rising or falling limb of other events (Fig. 24). As such, there is not a well-defined major flood crest although two of the crests are somewhat larger than the remainder. Hysteresis effects are still apparent, with sediment peaks preceding discharge crests by about 10 days, and being most pronounced when discharge events show rapidly increasing flows.



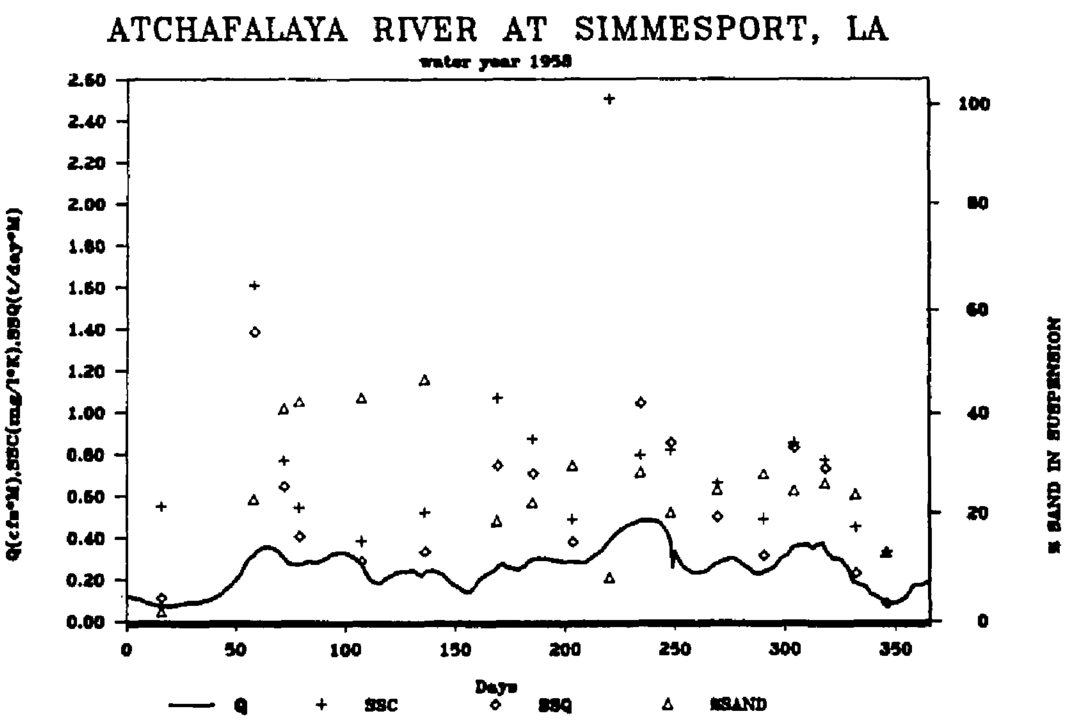


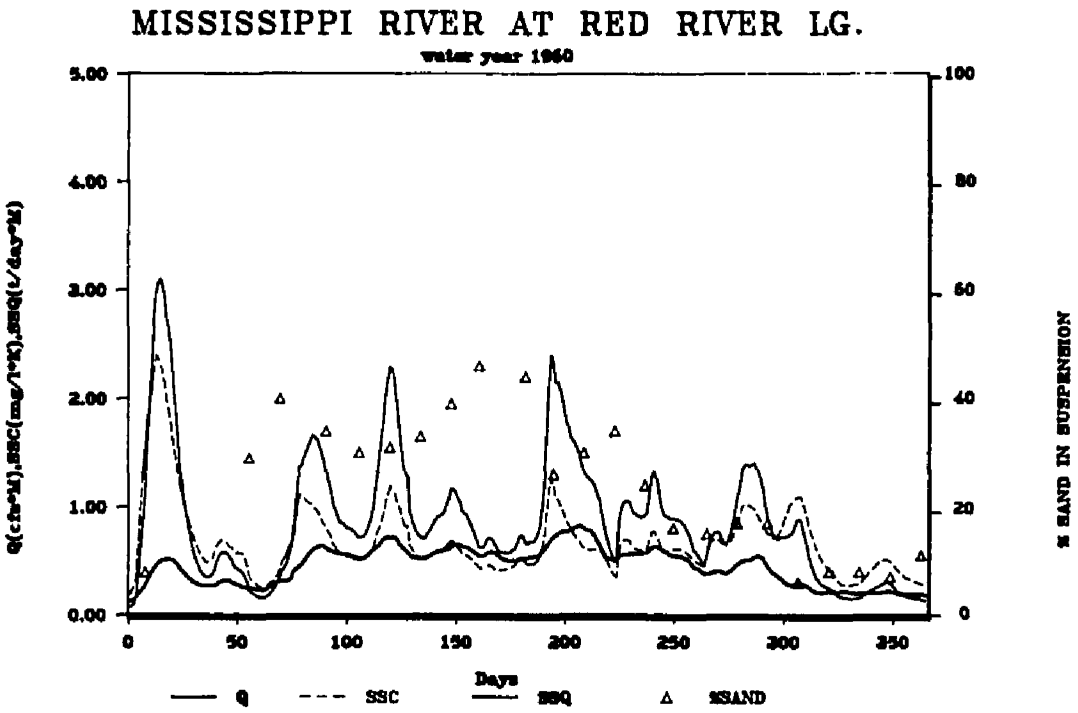
Figure 24. Discharge-suspended sediment relationships for water year 1958 on the Mississippi-Atchafalaya river system.

After large events, concentration troughs occur on the falling limb; otherwise, they coincide with discharge troughs. Concentration troughs are lowest during low discharges early and late in the water year, and next lowest on the falling limb immediately following the largest discharge crest. Percentage sand in suspension changes little with changes in discharge or with passage of sediment peaks, and is generally greatest during the winter season.

The annual flood on the Red River is the largest over the study period, showing a return period of about 50 years (Tables 9 and 10), and mean discharge is fifth highest for the study period. The sediment peaks on the Atchafalaya are greater during the two larger flood crests than the Mississippi (Fig. 24), which indicates that the increased magnitude of the peaks is probably augmented by sediment input from the Red River. Unfortunately, sediment data from the Red River are not available to confirm this inference.

Discharge-suspended sediment relationships in water year 1960

The return period of the annual flood on the Mississippi in water year 1960 is close to 1.25 years and the mean discharge is smaller than the average of the study period (Tables 9 and 10). The hydrograph is again quite chaotic and complex, showing several minor oscillations on a gradually rising and falling trend (Fig. 25). As with 1958, there is not a well-defined major flood crest although the annual peak in early spring and an event in early fall appear larger in magnitude than the remainder. Sediment leads the major flood crest by about 10 days, whereas the remaining sediment peaks mostly are concurrent with minor and moderate discharge fluctuations. The event in early fall shows the largest magnitude sediment peak, perhaps related to the greater rate of discharge increase compared to the other events and possibly to an excess of available sediment after the summer low water. Percent sand in suspension corresponds with discharge patterns somewhat, and shows a decline during passage of the peak associated with the major flood crest.



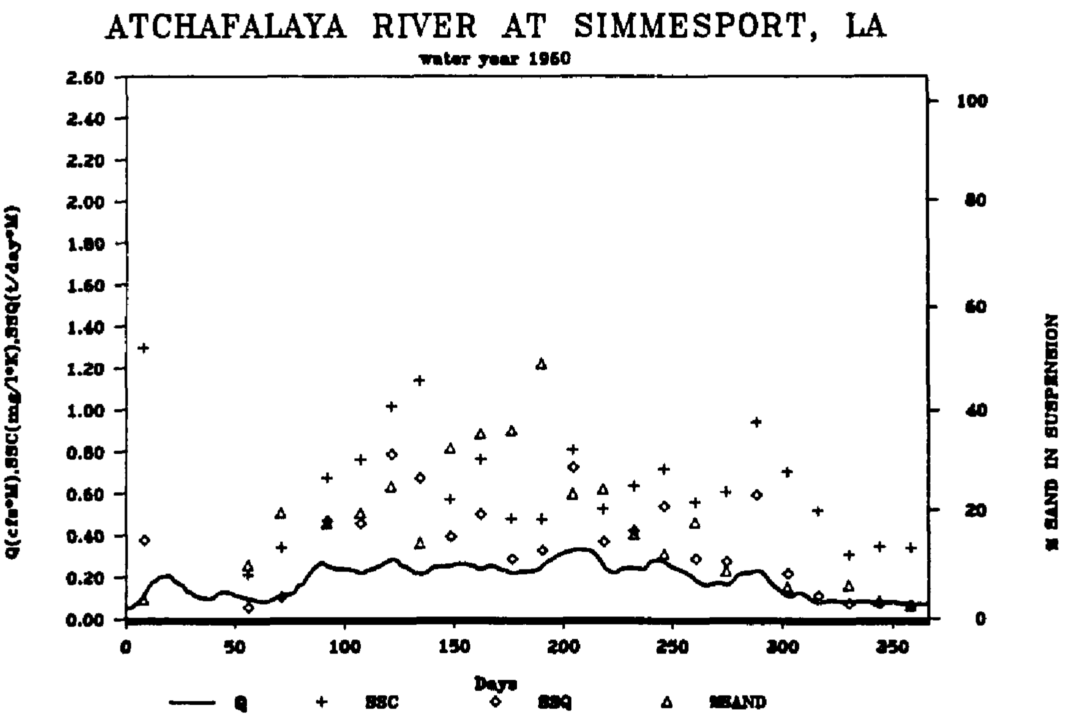


Figure 25. Discharge-suspended sediment relationships for water year 1960 on the Mississippi-Atchafalaya river system.

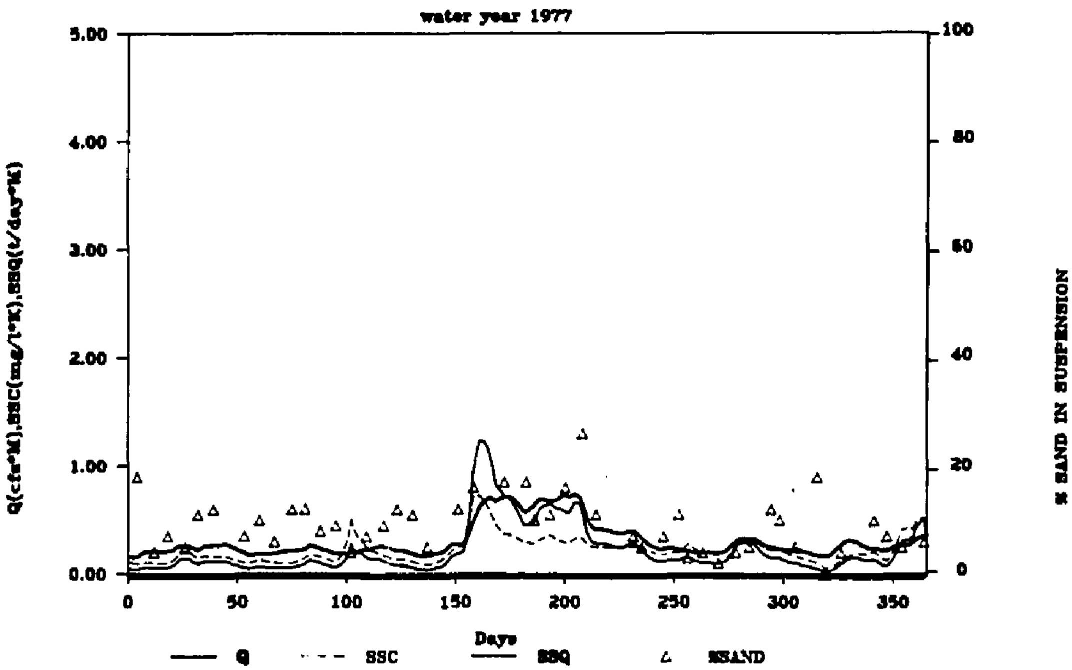
The annual flood on the Red River is relatively low, with a return period of less than 2 years (Tables 9 and 10) and the mean discharges are near the average. The peaks on the Atchafalaya that can be discerned from the given data are generally lower in magnitude than the Mississippi, which indicates that there is probably not much input from the Red River (Fig. 25). Percentage sand in suspension on the Atchafalaya basically corresponds with the discharge patterns.

Discharge-suspended sediment relationships in water year 1977

The third lowest annual flood on the Mississippi during the study period in water year 1977 shows a return period between 1.05 and 1.25 years (Tables 9 and 10). The hydrograph shows one major flood crest in late-winter early spring, with two nodes. The sediment concentration peak associated with the major flood occurs about 10 days before the flood crest, and decreases through the remainder of the event, although concentrations are much lower at low discharges (Fig. 26). Water year 1977 is generally devoid of secondary events, and the other times of increased concentrations are minor, generally during stationary parts of the hydrograph. Percentage sand in suspension appears to be greatest during the annual flood.

In relative terms, the Red River shows a larger annual crest, with a return period just less than 2 years (Tables 9 and 10). There are a significant number of flow events beginning in late fall and continuing through spring, that show corresponding high sediment maxima (Fig. 26). The largest sediment peak and discharge crest on the Red River are concurrent with the second node of the Mississippi discharge crest. This year, and several other examples, show that when discharges on the Red River are fairly high and exceed the relative magnitude of the Mississippi, the Red River typically has a very pronounced influence on discharge-suspended sediment relationships in the Atchafalaya.

MISSISSIPPI RIVER AT TARBERT LANDING



ATCHAFALAYA RIVER AT SIMMESPORT, LA

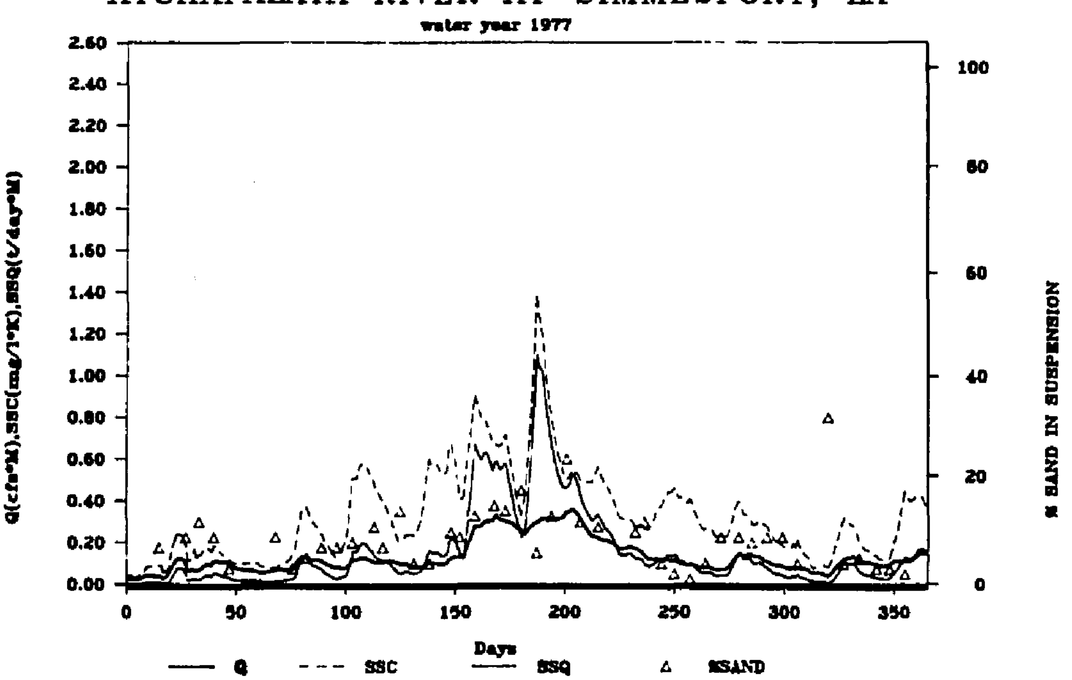
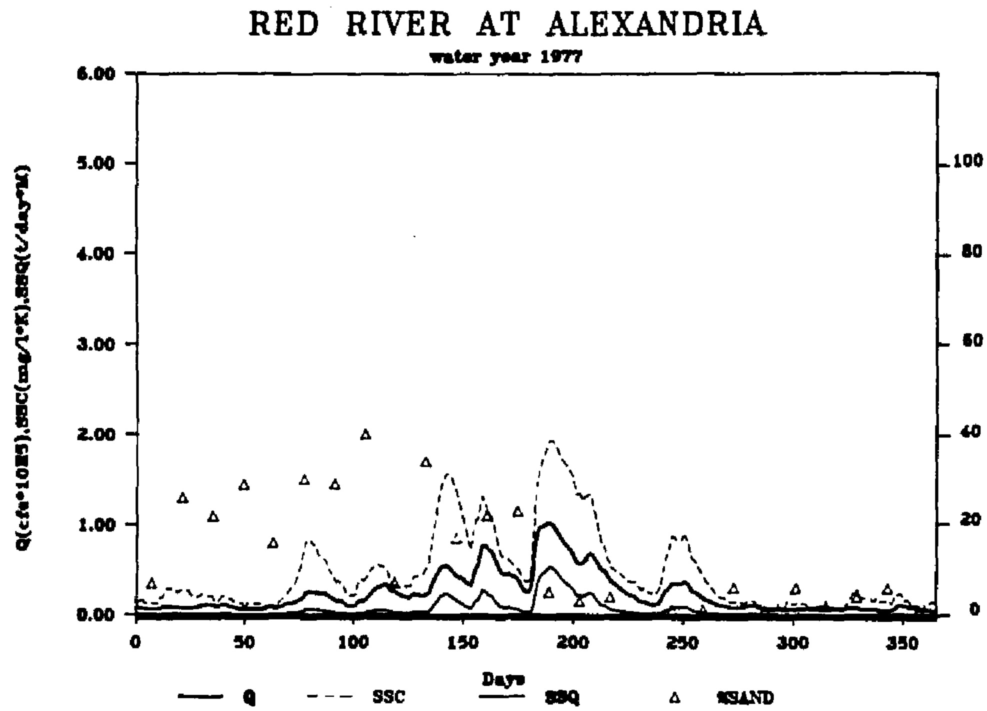


Figure 26. Discharge-suspended sediment relationships for water year 1977 on the Mississippi-Atchafalaya river system.



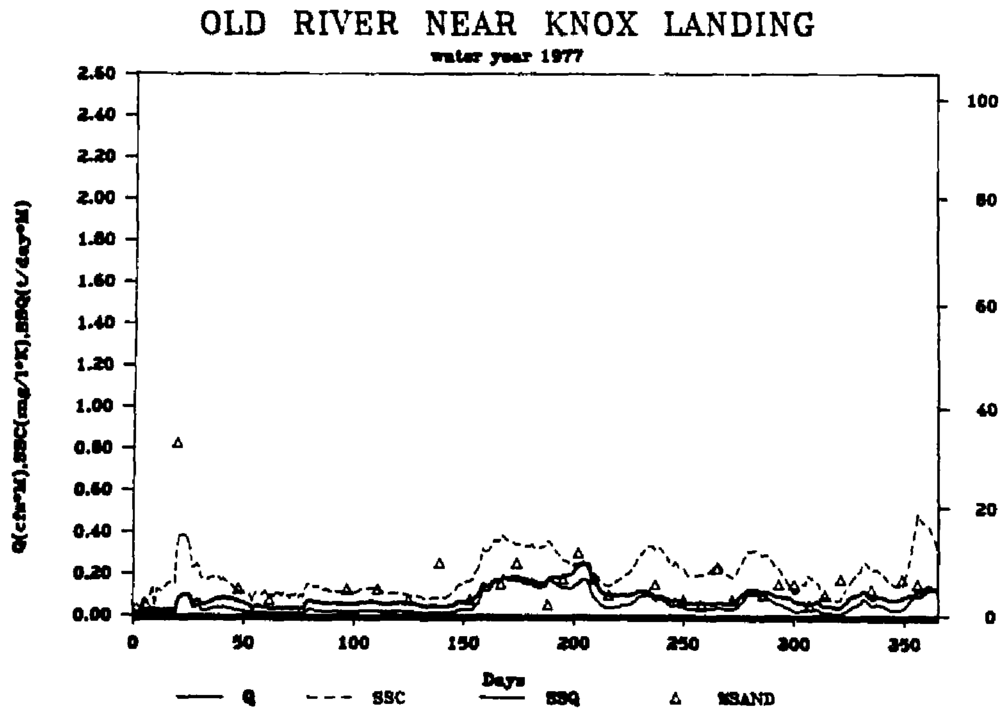


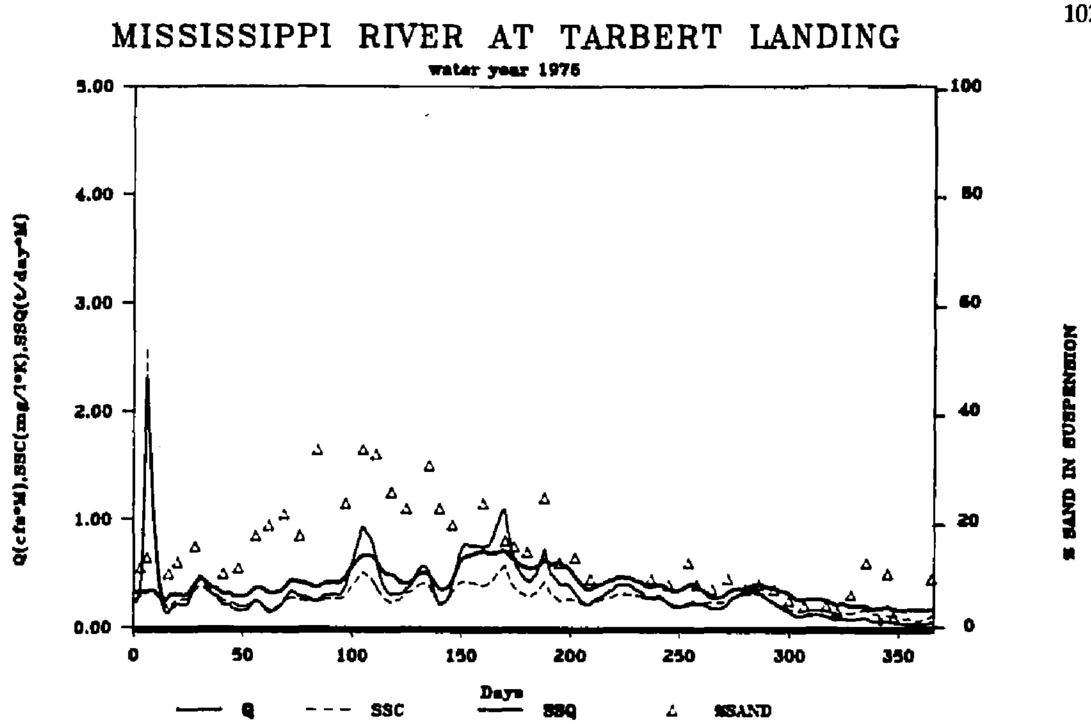
Figure 26 (cont.). Discharge-suspended sediment relationships for water year 1977 on the Mississippi-Atchafalaya river system.

On the Old River, concentrations increase during the major flood, but are generally lower than the Mississippi (Fig. 26). Secondary peaks during falling or relatively stationary discharges are more pronounced than on the Mississippi. The Atchafalaya shows peaks concurrent with both nodes of the major flood. The peak associated with the second node is the largest and relates to influx from the Red River. Many sediment peaks occur when discharges are stationary or falling on the Atchafalaya River, due in part to sediment contributions from the Red. Such peaks generally bear little relationship to discharge trends and thus are difficult to predict unless data from the Red River are available.

Discharge-suspended sediment relationships in water year 1976

Water year 1976 shows a return period between 1.05 and 1.25 years (Tables 9 and 10), the second lowest for the study period. The hydrograph showed one event much larger than the remainder on a gradually rising and falling discharge trend. The peak associated with the major flood is coincident with the crest, although a sediment peak of much larger magnitude occurs in early fall during virtually stationary discharges (Fig. 27). Some of the secondary crests also show associated sediment peaks. Percentage sand in suspension shows some relationship to discharge but appears to be largest in winter. The troughs following the major flood and secondary events are insignificant. Concentrations are lowest early and late in the water year when discharges are lowest, and appear to increase and decrease seasonally with rising and falling discharge trends.

Like the Mississippi, the annual flood on the Red River was relatively low, with a return period of less than 1.25 years (Tables 9 and 10) although the relative magnitude on the Red is larger. Sediment peaks and discharge crests correspond except for one minor peak in summer during falling discharges (Fig. 27). The largest event occurs in late winter as on the Mississippi, although it is much shorter in duration. There is also a succession of smaller events throughout the spring. In such circumstances, when discharges on both the Red and Mississippi are low, the Red River typically has a notable influence on the Atchafalaya.



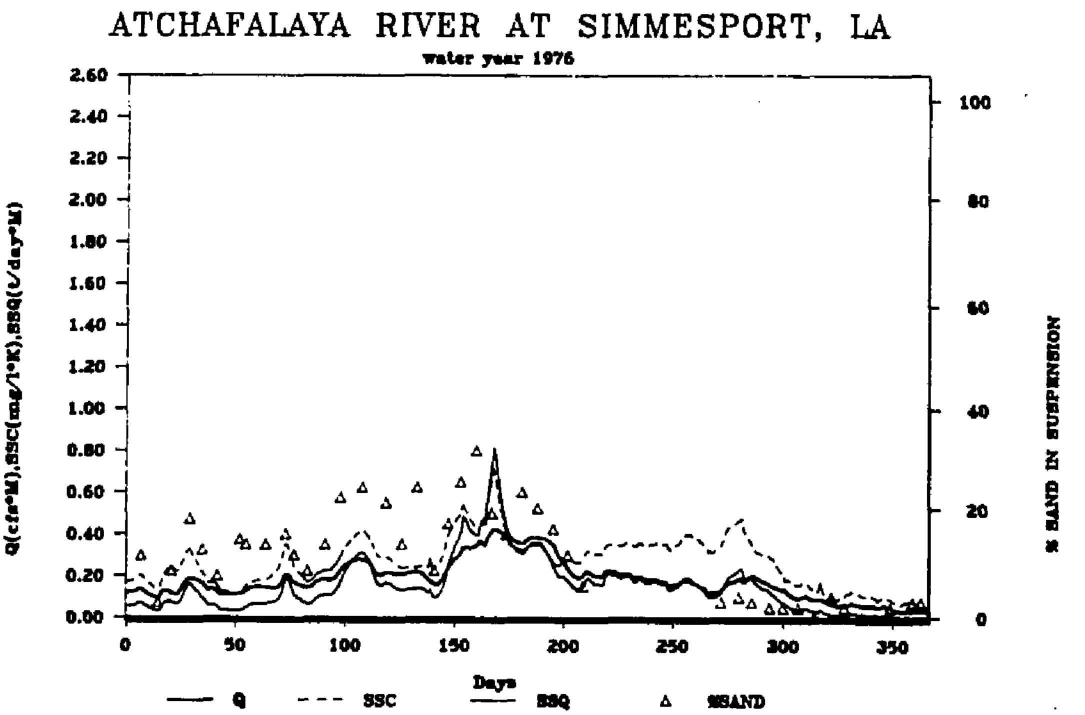
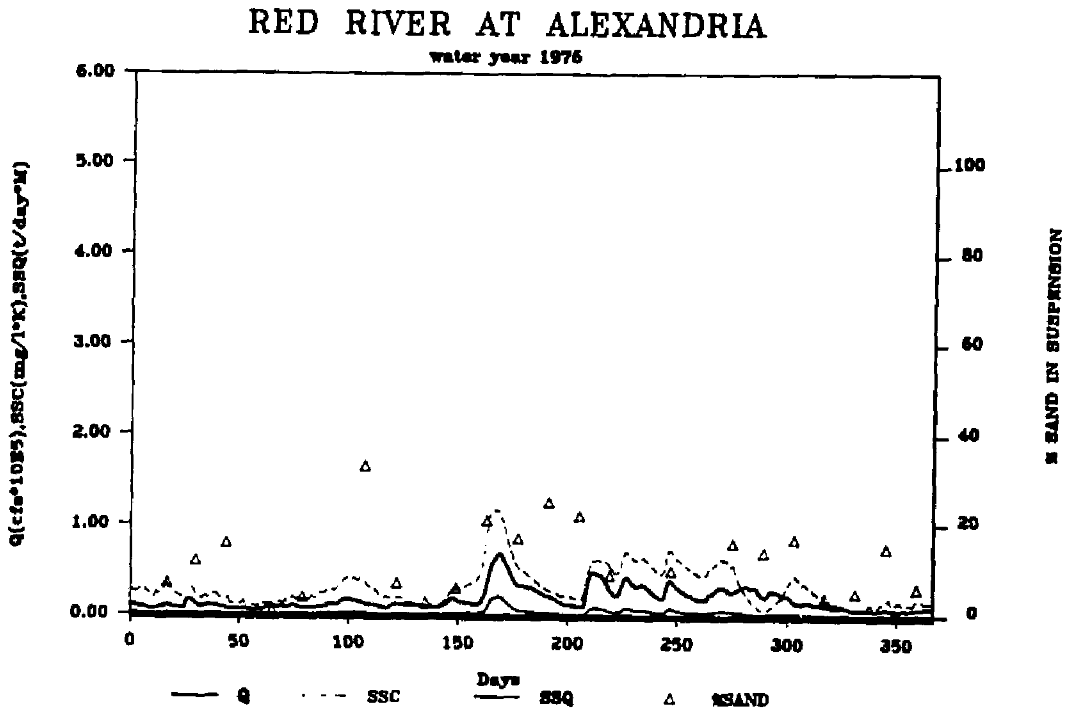


Figure 27. Discharge-suspended sediment relationships for water year 1976 on the Mississippi-Atchafalaya river system.



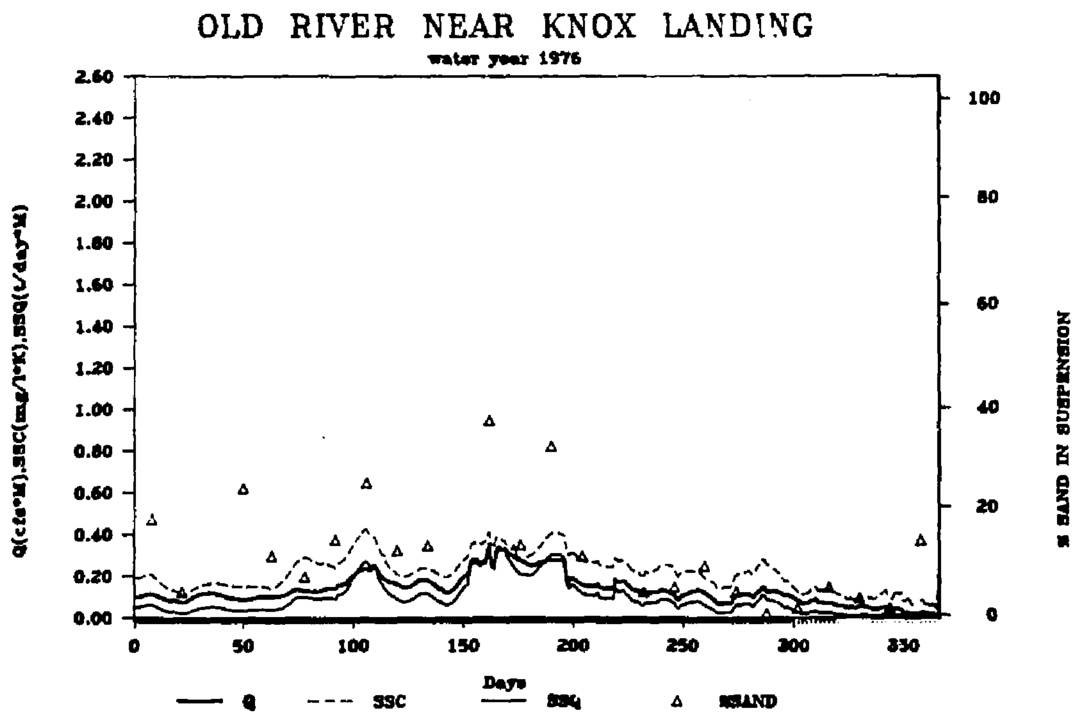


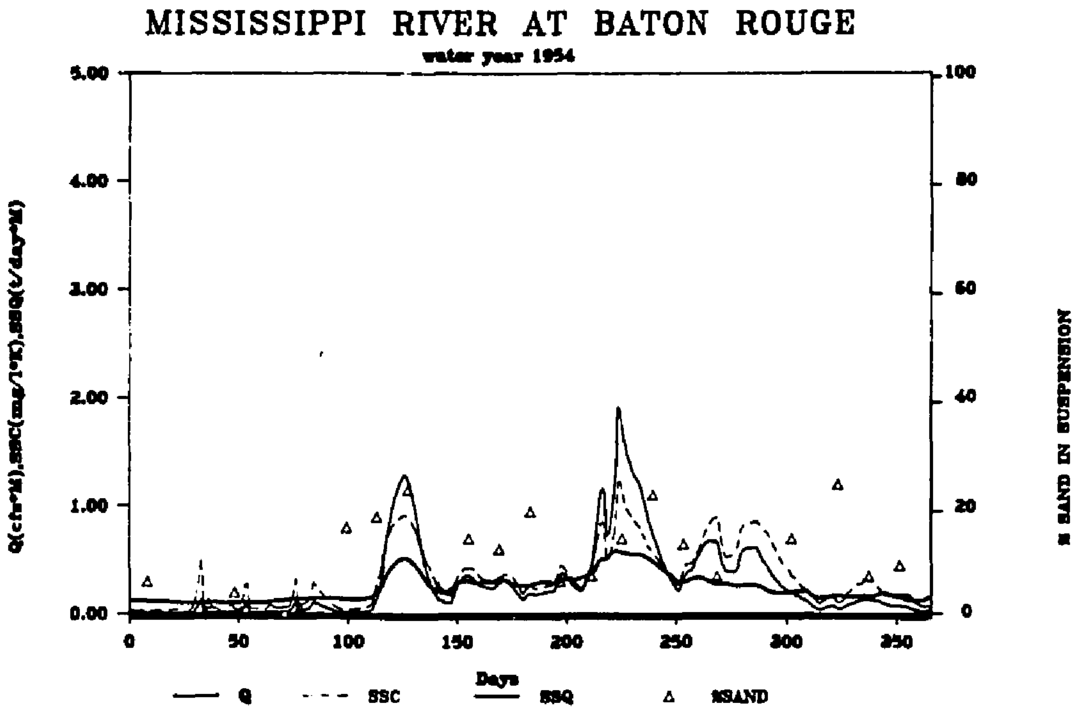
Figure 27 (cont.). Discharge-suspended sediment relationships for water year 1976 on the Mississippi-Atchafalaya river system.

The Old River Outflow Channel shows virtually the same pattern of sediment peaks as the Mississippi except for the absence of the unusual peak in early fall (Fig. 27). The Atchafalaya also does not show the additional peak, however, it shows increased sediment activity during the major flood crest and throughout the spring when discharges are declining. These differences are all attributable to contributions from the Red River, even though its discharges are low. Percentage sand in suspension on the Old and Atchafalaya rivers is at a maxima in winter during high discharges.

Discharge-suspended sediment relationships in water year 1954

The lowest maximum and mean discharge during the study period occur in water year 1954, with a return period for the annual flood between 1.003 and 1.05 years (Tables 9 and 10). The sediment peak associated with the major flood is the largest in this year and is coincident with the discharge crest (Fig. 28). Concentrations are also high on a secondary crest in the winter and on the falling limb in the late spring and early summer. Some minor peaks in fall are depicted while discharge changes are minimal although it appears there is little data to confirm their presence. Percentage sand in suspension is greater during high discharges and shows little change with the passage of sediment peaks.

The annual flood on the Red River in water year 1954 has a return period of less than 2 years (Tables 9 and 10) and a mean flow well below the average, but is of greater relative magnitude than the Mississippi. The largest sediment peak on the Atchafalaya occurs during the major flood, but is much larger in magnitude than the Mississippi, and therefore may be augmented by the Red River (Fig. 28). The next largest peak on the Atchafalaya occurs during the secondary crest in winter as on the Mississippi and is similar in magnitude. Maxima of percentage sand in suspension appears to lag the discharge crests on the Atchafalaya although the sand concentrations are much larger during the crests.



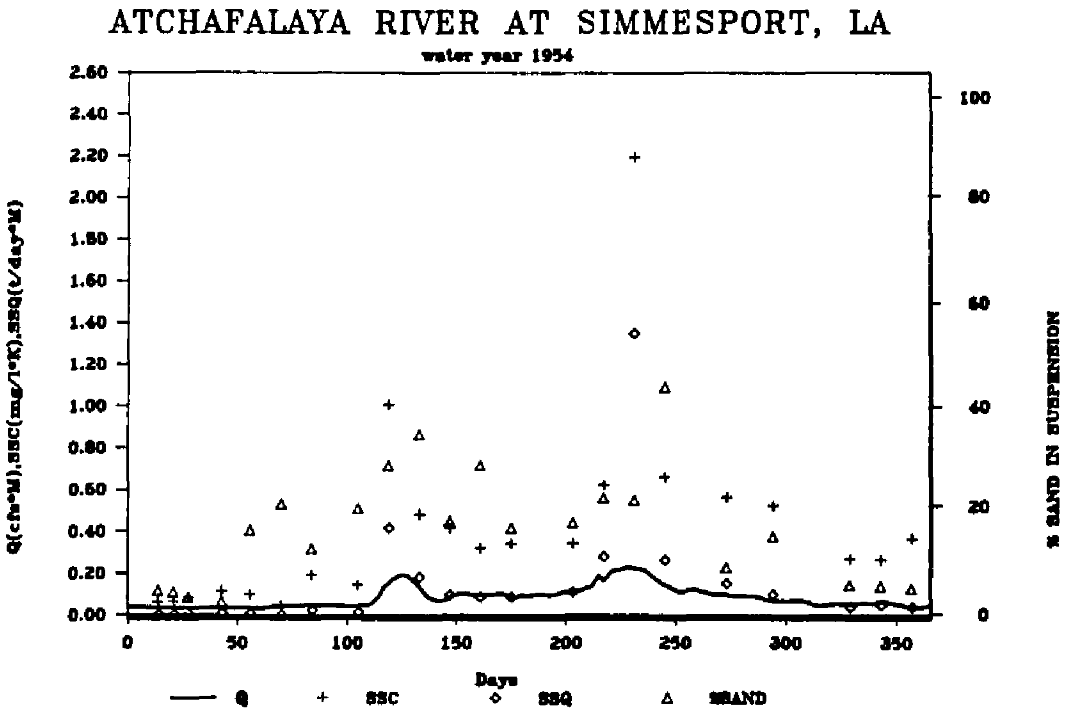


Figure 28. Discharge-suspended sediment relationships for water year 1954 on the Mississippi-Atchafalaya river system.

Synthesis of system behavior during the annual cycle

The conceptual diagram proposed from the empirical relationships (Fig. 18) is generally valid for years in which there is one major flood. Hysteresis effects overwhelmingly favor a lead of the sediment peak on the rising limb before the discharge crest (e.g. Everett, 1971; Wells, 1980) and not a lag of sediment after discharge as noted in some previous investigations (WES, 1939; Allen, 1974) on bivariate plots. The lead is greatest for the highest discharge years where sediment peaks sometimes precedes discharge crests by two months; the lead generally decreases with decreasing maximum discharge such that in low discharge years the sediment peak and discharge crest coincide.

High, intermediate, and low discharge years differ in the amount of time spent in the various domains that categorize discharge-sediment behavior. Because the lead of the sediment peak is typically greater in high discharge years, then the amount of time when discharge is rising and sediment is declining or Type QRCF is greater. As the annual discharge magnitude becomes smaller, hysteresis is not appreciable and proportionately more of the year is split between the Type QRCR and QFCF domains.

The Red River, in contrast to the Mississippi, shows discharge-sediment relationships almost exclusively in the Type QRCR and QFCF domains. When the Mississippi flow is high and the Red River is low, the Red shows little influence on the Atchafalaya. If the Mississippi and Red are both high or both low, the Red generally shows notable influence on the Atchafalaya. When the Mississippi is low and the Red is high, even though the Red's discharge is typically a fraction of that diverted through Old River, the influence of the Red on the Atchafalaya is quite pronounced. Depending on the timing of the discharge events in the Red River, it may either augment an existing peak from the Old River or provide sediment to the Atchafalaya at times of falling or relatively stationary discharges. For this reason, the Atchafalaya shows more peaks at stationary or falling discharges than the other locations.

The amount of time spent in the fourth domain, Type QFCR, is not well-predicted by the conceptual diagram and similarly is often difficult to predict in the physical world. Such events may represent tributary contributions, such as from the Red to the Atchafalaya, and therefore may be predicted if discharges of various tributaries are incorporated into time series modeling, or they may represent bank failures, in which case they are associated with high moisture levels and pore water pressures in the bank and often occur during rapid drawdown. Sediment peaks on the falling limb, or otherwise not associated with a discharge increase, are not exclusive to high discharge years as depicted in the conceptual diagram; these peaks also occur during years when the annual flood magnitudes are low, or somewhere in between.

In years in which there are multiple flood events, such as in 1983 and years of compound floods, the time sequence of discharge events in the annual cycle also influences discharge-sediment relationships. Successive events progressively cause the available sediment supply to decline, such that the peaks tend to decrease in magnitude, duration, and/or arrive earlier on the rising limb and troughs tend to decrease in magnitude, increase in duration, and/or arrive earlier during the flood so that during large events troughs often coincide with discharge crests. If the secondary peaks arrive earlier in extremely high discharge years, they are sometimes more prominent than peaks associated with the major flood because of the limited availability of supply.

In years with the largest floods, that show return periods greater than 20 years, or in years in which there are multiple flood events of appreciable magnitude early in the year, sediment supply is favored during the winter season. During most years which have smaller floods with return periods generally less than five years, the supply is not consumed by the early flows so that sediment follows discharge patterns, which generally show maxima in spring.

Most of the sediment peaks associated with the major flood are composed predominantly of silt and clay, as the percentage of sand decreases with passage of the peak. The silt-clay dominated sediment peak is thereafter followed by an increase in sand percentages. Many of the secondary sediment peaks are also dominantly silt and clay. The initial peak after low water, unlike the others, generally shows an increase in sand content with passage of the peak, and as such may be evidence of basal clean-out of disturbed bank material.

One caveat associated with interpretation of these time series is that the form of the graphs might show some differences if a nonlinear, instead of a linear, function were applied to discharge-suspended sediment relationships. This would not be a problem in the Red River, where the model forms are linear, but might introduce additional sources of error on the Mississippi, particularly when sampling is relatively infrequent. The application of nonlinear functions might help improve the accuracy of discharge-suspended sediment relationships and the annual loadings which are presently computed using linear functions.

DISCUSSION

Empirical relationships

Significant findings

Differentiating the sediment concentration into components by particle size reveals that the silt-clay component generally responds differently to discharge changes than the sand component of the suspended sediment on the Mississippi below the diversion, the Atchafalaya at Simmesport, and the Old River Outflow Channel. The silt-clay component fits nonlinear functions whereas the sand component is more nearly linear. The total suspended sediment concentration is a composite of these different components, but more closely resembles the plots of silt-clay concentration, which constitutes the larger proportion of the total concentration. The nonlinearity of suspended silt-clay concentration appears to be related to its limited availability locally and upstream and its transport through the system by the flushing process.

The Mississippi at Belle Chasse is unlike upstream at the Mississippi below the diversion in that the explanation of the variance for both the linear and quadratic models is much better for several reasons. The plots show reduced scatter compared to upstream because of the shorter period of record at Belle Chasse. The models' forms also show differences probably because of changes in hydraulics from upstream to downstream, and the increased availability of silt and clay locally downstream. Hydraulic changes include the lower velocities at low discharges downstream associated with the deeper channel, although differences in cross sectional area become smaller with increased discharges because of the greater stage variations upstream. While the silt-clay in suspension at the Mississippi below the diversion is acquired mostly from upstream locations, Belle Chasse shows larger quantities of silt-clay on the channel bed and greater quantities of silt-clay may be provided through resuspension.

The Red River is quite unlike the Mississippi-fed locations in that the relationships between discharge and the sediment concentration parameters are all highly linear. Suspended sediment and silt-clay concentrations on the Red River at Alexandria also show the least scatter, and the highest maximum concentrations of the rivers and sampling locations in the study area. Probable reasons for the better explanation include the shorter period of record, which reduces the effects of nonstationarity, and an abundance, as contrasted with limited availability, of silt and clay from the basin and/or the channel perimeter. Some explanations for the increased silt-clay availability include differences in hydraulics, climate, vegetation, geology, and the extent of bank protection, although these are by no means the only factors.

Quadratic log-log functions produced better correlations than linear log-log functions in the Mississippi, Atchafalaya, and Old rivers as measured by the comparative test of the models using the F^* statistic. The model differences are highly significant for most parameters, particularly for the silt-clay and total suspended sediment concentration. Suspended sand concentration and suspended load also show improvements with quadratic models, particularly where concentration and load are decreasing at high discharges. Downstream at Belle Chasse, the quadratic log-log models also improved correlations for most discharge-suspended sediment relationships, particularly between discharge and percentage sand in suspension. The model differences are not significant for the Red River at Alexandria, in which discharge-suspended sediment relationships are fairly well explained by the linear models.

Correlations were not particularly high as the observed sediment concentration ranges considerably for a given discharge, largely because physical factors other than discharge influence the suspended sediment concentration. Scatter in discharge-sediment relationships may be produced by factors such as variations in the flood peak magnitude, antecedent moisture conditions, season and water temperature, bank failures, supply limitations, varying patterns of tributary inflow, land cover, land use, dredging, and other dynamic and non-stationary parameters in the system (Guy, 1964; Walling and Gregory, 1970; Walling and Teed, 1971; Porterfield, 1972; Allen, 1974; Walling, 1977).

Errors in the field and laboratory may also introduce scatter. However, considering all the possible factors that influence sediment and the sources of variation across such a large basin, and the complex and dynamic nature of the system, correlations are much better than might be expected.

Relevance to existing conceptual framework

The state of knowledge regarding statistical relationships between discharge and sediment shows the need for a substantial number of site investigations with large and long-term data bases, and for revision of existing approaches and concepts. In many studies published recently (e.g. Komar, 1988), the ubiquitous regression of the two dependent variables against each other is still used as a basis for description of sediment transport processes. While there are other studies that recognize concentration as the preferred variable to examine, this concept needs to be more actively promoted, given the statistical inferiority of the alternative.

The standard rating curve or log-log relationship that has been used in previous studies (Sedimentation Seminar, 1977) would often underpredict sediment concentration during the first part of rising discharge and overpredict immediately before and during the flood crest and falling discharge, particularly during high discharge years. Unlike the case of smaller rivers, where differentiation by stage and seasonal trend has produced improved results (Walling, 1974; 1977a), differentiation of measurements by stage trend and season on the Mississippi-Atchafalaya river system would not considerably improve the regression relationships because hysteresis causes data to counter expected trends. The successful application of multivariate relationships would require further subdivision into other categories based on supply, possibly the rate of change of discharge with time, and other factors.

Also, there has been a greater need to examine the silt-clay and sand behavior separately to understand differences in transport of these components from a conceptual viewpoint. Very little is known regarding the behavior of cohesive as opposed to noncohesive materials (Wolman, 1977).

Suspended sediment measurements encompass the suspended fraction of the bed material plus the wash load; it is generally thought that the bed material discharge is truly dependent on the flow rate, whereas it is thought that the washload does not exhibit a clear functional relationship with the flow rate (Colby, 1963; Graf, 1971; Komar, 1988). Inferences have been made that since there appears to be no relationship in specific rivers with silt-clay concentration vs. discharge, that this concept holds true for rivers in general (Komar, 1988). This study on the Mississippi-Atchafalaya system shows that this type of generalization is invalid, as the silt-clay may not fit linear functions well but can certainly be improved with nonlinear functions. If it is the dominant component, as in many locations, it controls the shape of the relationship between discharge and suspended sediment, and therefore deserves considerably more attention. There is a need for continued work and the use of the silt-clay and sand divisions in many rivers before applying concepts from one river to all rivers.

Some causes for nonlinearity in fluvial behavior have been suggested by a few researchers including Church (1967) and Richards (1973). With other types of hydraulic and geomorphic data, they observed changes of roughness and channel geometry with discharge. Richards (1973) suggested that hydraulic geometry relationships, especially velocity and depth with discharge, did not fit simple linear log-log functions, and applied a quadratic log-log function in his study. He suggested that it was possible that sediment data would follow such functions also. In addition, Richards (1984) has also discussed the use of dQ/dt (rate of discharge change with time) as an important variable to be considered in discharge-sediment relationships. While discharge-velocity relationships in the Mississippi may not be nonlinear, there is a need for further work to confirm this and to analyze the relationships of suspended sediment with the rate of discharge change with time.

The physical explanation for the nonlinearity of these relationships appears to be largely due to the limited silt-clay availability in the Mississippi system, but could also be related to other types of discontinuities of hydraulic, geomorphic, and sedimentologic factors, or combinations of these conditions that have not been given specific attention in this study. Hydraulic discontinuities may be a result of the change from lower to upper regimes of flow, which produces attendant changes in sediment transport, bedforms, and roughness. Geomorphic discontinuities include the change from below- to above-bankfull flow conditions. Sedimentologic discontinuities include the decline of supply of specific sizes of material available for transport. Human-induced changes in the basin including implementation of reservoirs, construction of levees, revetments, and cutoffs, and other changes in land use may also have changed the sediment availability over time. All of these would need to be examined in greater detail before the relative importance of these explanations could be assessed.

Local applications

The effectiveness of controlled diversion and marsh management projects could be improved by releasing flows or allowing flows to enter during those conditions that promote land-building when concentrations are typically highest. Discharge-sediment relationships vary at different locations, and management of the river requires considering differing local conditions. For example, in the Mississippi River maximum suspended sediment and silt-clay concentrations occur at intermediate discharges near Tarbert Landing but occur at high discharges at Belle Chasse. The percentage of sand in suspension at any time can also be estimated by using the statistical relationships established in this study.

Other applications include predicting sediment supply to the coast or extrapolating delta growth under various hypothetical discharge scenarios, and other types of planning for future management. Assessments of sediment-associated pollutants can be improved by knowing the concentrations and loads of the silt-clay and sand components, which follow different functions, at various discharges and locations.

Temporal and spatial variations

Significant findings

The Mississippi-Atchafalaya system is a highly dynamic and complex river system whose behavior changes from year-to-year such that inferences regarding hydrologic and sedimentary processes are best made from large and long-term data bases. Of the four rivers that comprise the system, the Mississippi and Red rivers provide contributions to the others and therefore act quasi-independently; the Mississippi shows the least annual variation in discharge and sediment concentration, whereas the Red is highly episodic and shows the greatest annual variation, with sediment concentrations being several times greater than the Mississippi. The Old River Outflow Channel typically has slightly lower concentrations than the Mississippi, perhaps due to the angle of diversion and the higher bottom elevation of the diversion channel, which may cause mean concentrations to be lower. The Atchafalaya merges the flow and sediment of the Old River Outflow Channel and the Red River, and may be dominated by one or the other in a given year; the Red provides only 15 to 50%, and averages 31.1%, of the discharge, but because of its greater concentrations, averages 42.0% but supplies as little as 10% and as much as 70% of the sediment load on the Atchafalaya.

Mean discharges show declining trends for the Old River, but does not show statistically significantly trends at other locations. The Mississippi shows highly significant declining trends in mean suspended sediment load, although the other rivers, including those that it feed, do not. The Mississippi, Red, Old, and Atchafalaya rivers all show significant or highly significant declining mean suspended sediment concentrations, which are probably due largely to human modifications in the basin including dams and revetments. The Mississippi and the locations it feeds in most cases show significant or highly significant serial dependence in discharge and concentration, which implies influence from antecedent conditions. Suspended load only shows serial dependence in the Mississippi.

Consistent patterns in the temporal relationships of discharge and sediment on the Mississippi-Atchafalaya system are manifest when interpreting discharge years from high to low sequentially. These differences are most pronounced on the Mississippi and Old River Outflow Channel, and are often present on the Atchafalaya. During high discharge years, peak sediment concentration and load often occur on the rising limb during the first major increase in the hydrograph, and precede the discharge crest by several weeks to two months, resulting in a decline in sediment supply by the time the discharge crests. Troughs of sediment concentration generally coincide with, or slightly lag streamflow crests during high discharge years. As maximum annual discharge decreases, suspended sediment peaks occur closer to and ultimately coincide with the major flood crest; concentration troughs typically coincide with discharge troughs.

Depending on the timing of the discharge events in the Red River, it may either augment an existing peak from the Old River or provide sediment to the Atchafalaya at times of falling or relatively stationary discharges. For this reason, the Atchafalaya shows more peaks at stationary or falling discharges than the other locations. When the Mississippi flow is high and the Red River is low, the Red shows little influence on the Atchafalaya. If the Mississippi and Red are both high or both low, the Red generally shows notable influence on the Atchafalaya. When the Mississippi is low and the Red is high, even though the Red's discharge is typically a fraction of that diverted through Old River, the influence of the Red on the Atchafalaya is quite pronounced. Hysteresis effects and differences in timing between high, intermediate, and low discharge years are not as apparent or pronounced on the Red River, because discharge and sediment peaks are nearly coincident in time. Such effects might be more apparent if sampling were more frequent and if the timescale depicted for events were shorter.

Seasonality in the Mississippi-Atchafalaya system is also apparent in discharge, suspended sediment load, concentration and its components, and percentage sand in suspension. Discharges and percentage sand in suspension are typically greatest in winter and spring on the main system. During high discharge years, more sediment is available in winter than in other seasons, as at such times the sediment maxima generally precede discharge maxima by several months. In low and intermediate discharge years, the sediment maxima coincide or occur just shortly before the discharge maxima, typically during the spring and early summer months.

The absolute and relative timing, magnitude, and form of the sediment peaks in the Mississippi, Atchafalaya, and Old rivers at times were similar, but sometimes underwent considerable modification as they cascaded from one location to the other. Usually the peaks were similar to their sources. For example, timing, magnitude and form of sediment peaks on the Old River Outflow Channel were similar to the Mississippi. The Atchafalaya sediment peaks were a hybrid of the Old River Outflow Channel and the Red River, and may have been dominated by one or the other in a given year. Differences in the timing, form, and magnitudes of peaks that could not be explained by the sources, implied that other factors, including differences in sediment contributions from snowmelt and runoff processes, seasonality of erosion, settling, resuspension, undocumented tributary contributions, bank failures, supply limitations, and human activities were involved. In some cases, they could also be attributed to sampling schedule differences or various types of measurement error.

Most of the sediment peaks associated with the major flood are composed predominantly of silt and clay, as the percentage of sand decreases with passage of the peak, and increases shortly after its passage. Many of the secondary sediment peaks are also dominantly silt and clay. The initial peak after low water, unlike the others, generally shows an increase in sand content with passage of the peak, and as such may be evidence of basal clean-out of disturbed bank material.

Different timescales of reduction of sediment supply were observed in the Mississippi-Atchafalaya river system, being most pronounced on the Mississippi. There was an overall decrease from the beginning to latter part of the record over several decades as shown by the trends, due largely to human modifications in the drainage basin. Secondly, at times multiple large floods within a single year appeared to reduce available sediment from the channel and basin surface. Reduction in supply also may be connected with physical thresholds; these thresholds often occur within the intermediate or high discharge range, and are mostly related to silt-clay availability. Sand is still abundant both by percentages and absolute concentration as discharge increases, even though additional quantities of easily mobilized material may be available early in the year and are removed by basal clean-out. The discharges at which concentration maxima were reached were similar throughout the study period, however, the corresponding magnitudes of concentration, the response variable, have decreased throughout the study period. Successive events progressively cause the available sediment supply to decline, such that the peaks tend to decrease in magnitude, duration, and/or arrive earlier on the rising limb and troughs tend to decrease in magnitude, increase in duration, and/or arrive earlier during the flood so that during large events troughs often coincide with discharge crests. If the secondary peaks arrive earlier in extremely high discharge years, they may be more prominent than peaks associated with the major flood because of the limited availability of sediment supply.

Relevance to existing conceptual framework

Some existing concepts of sediment movement in rivers in general and specifically for the Mississippi-Atchafalaya river system can be evaluated in light of this work. Some of these concepts include timing in large as contrasted with smaller rivers, timing between sediment parameters and discharges in terms of respective directional changes, and in terms of the relative timing of the sediment wave and flood wave.

Unlike Knighton (1984), who suggested that in large basins the sediment peak tends to lag the discharge crest, this and other studies show that sediment peaks in large rivers may show a pronounced lead before discharge crests. Sediment peaks often preceded discharge peaks by 40 to 70 days on the Mississippi and Atchafalaya for large events, occurred several weeks before the discharge peaks on the Oubangui, and about two months before discharge peaks on the Congo in 1987 (Olivry et al., 1988). Such great lengths of time between sediment peaks and discharge crests may be partly related to the large river size, also to the flood magnitude, but perhaps most importantly reflect a decline in the availability of silt-clay material for transport. Hysteresis effects might therefore be less pronounced in semiarid climates and in non-revetted channels where sediment supply is greater.

The various types of discharge-sediment relationships observed in the Mississippi-Atchafalaya river system may be applicable to interpreting periodic phenomena in other rivers. The first type of behavior, with both discharge and concentrations rising (Type QRCR), is more common in the early stages of a large flood event or throughout most of the time during a smaller flood event, due to flushing or less commonly may be related to tributary contributions, lateral bank erosion, and basal cleanout during rising stages. The second type, with both discharges and concentrations falling (Type QFCF), is probably the most common during the falling limb of a hydrograph, although dilution from tributaries may aggravate such conditions. Both types of behavior in sediment concentration appear to be directly related to discharge, and possibly the rate of change of discharge with time, and the acceleration of change. The third type of behavior, with discharges rising and concentrations falling (Type QRCF), is most common on the rising limb of large magnitude floods in high discharge years, and is also related to the variables above, the achievement of physical thresholds of various types, and a decline in supply. This phenomena is important in the Mississippi-Atchafalaya system and possibly other large rivers because of the great lengths of time between sediment peaks and discharge crests, but may not be very important in other types of rivers where supply is abundant. The fourth type of behavior, with discharges falling and concentrations rising (Type QFCR), is typically shorter in duration, is most common late or early in the water year, and occurs in years with flows of various magnitudes. Physical causes include numerous natural and human-induced processes such as contributions from sediment-laden tributaries as discharges were falling on the main channel, a succession of bank failures after floods related to wetting and drying of batture soils, human activities such as channel dredging which is typically done during low water, and turbulent fluctuations of stream velocity. Existing data show that this phenomena is important in the Mississippi-Atchafalaya system, although it may be less important in basins without sediment-laden tributaries, major human modifications, bedrock as opposed to alluvial rivers, or coarse-grained streams. More could be learned about the relative importance of each type of behavior by quantifying the timing, magnitudes and frequencies of these categories on time series graphs in the Mississippi-Atchafalaya system and applying this approach to other rivers.

The relative movement of the floodwave and sediment wave are poorly understood in the Mississippi-Atchafalaya system and rivers in general. Other studies on the Rio Grande (Leopold and Wolman, 1956) and on the Bighorn (Heidel, 1956) have commented that, in floods, the peak sediment transport rate led the peak of water discharge upstream, but lagged the floodwave downstream. A study conducted on the Mississippi at Mayersville near Vicksburg (USWES, 1939) also describes how the sediment concentration peak lagged the discharge peak in the 1937 flood. Although Allen (1974) proposed from this data that Mayersville may be sufficiently far downriver to show the progressive downstream lag in sediment, this study shows that even further downstream at Tarbert Landing, sediment concentration and transport tends to lead discharge during floods much more than it lags. As far downstream as Belle Chasse, however, resuspension of silt and clay from the channel perimeter becomes an important mechanism of sediment transport, and results in two types or peaks, one related to flushing as at upstream and another marking the initiation or maximum of resuspension. Further work using historical and modern data is recommended if concepts regarding the relative movement of sediment and flood waves were to be reassessed; some answers could be provided if timing of the flow and sediment peaks during high discharge events were examined and compared at several locations along the river.

Some researchers have also observed that the suspended sediment concentration generally attenuates more slowly than the water discharge (Graf, 1971), using several examples described previously (Einstein et al., 1940; Jarocki, 1963; Nordin et al., 1963). This phenomena is certainly not true of the Mississippi, particularly in recent years which show very acute sediment peaks and even several years ago when more sediment was available; it is possible that such effects pertain mostly to smaller rivers, those with more supply, or those which carry greater volumes of coarse material.

Large rivers in flood may show several important maxima (e.g. two, three, or more) in each of several parameters that influence sediment transport, and it may not be possible to correlate any of them with the greatest sediment motion (Tanner, 1986). This, therefore, presents problems for modelling. If special functions were developed to incorporate phenomena including the timing and thresholds at which maxima are achieved and the nonlinear behavior of some of the variables, modelling of sediment transport in the Mississippi-Atchafalaya system could be attempted. However, as Pickup (1988) describes:

> "Modelling the distributed behavior of large river systems with analytical or quasianalytical models poses special problems....The procedure is complex, computationally expensive and prone to considerable error. Individual models build up the total system behavior from the behavior of a system's constituent parts so errors have a tendency to compound. It is also very difficult to synchronize the temporal behavior of different parts of the system correctly. For example, because water and sediment travel at different speeds, a flood wave may overtake the pulse of sediment it transports from upstream source areas, producing new erosion further downstream as new material is entrained. If the behavior of different parts of the system is not properly synchronized, model results are likely to be inaccurate. A further problem is the amount of data required to run a model of a large system. Few organizations have the resources to collect such data and the cost can rarely be justified."

The suggestions described by Naden (1988) of splitting the data into two distinct functions associated with the rising limb and with the falling limb (e.g. Walling, 1977) or building a second independent variable such as a change in flow in the equation (e.g. Richards, 1984), would be problematic in large rivers since the sediment peak often leads the discharge crest and may lead, lag, or coincide with the maximum rate of discharge change.

Local applications

The Mississippi-Atchafalaya system operates very differently between high and low discharge years, and therefore should be managed very differently, for controlled diversions and for other types of coastal restoration efforts. During high discharge years, if it were desired to maximize sediment concentrations, water should be diverted or allowed to enter project areas on the rising limb of flood events, generally in winter and early spring, with releases earlier on the limb with floods of larger magnitude. If it were desired to minimize sediment concentrations, water should be diverted or allowed to enter project areas at or shortly following peak discharges. During low discharge years, if it were desired to maximize sediment concentrations, diversion or entry should be coincident with the discharge maxima, generally in spring or summer, and possibly not at all in droughts.

The documentation of human-induced changes in the system also provides information on concerns for future management of the system. Construction of a number of diversions will certainly have a local effect on the discharge and sediment regime of the river and these changes should be monitored to avoid exacerbating existing problems. The existing and planned construction of locks, dams, and revetments on the Red River will likely cause decreased concentrations and loads in the lower Red and Atchafalaya, and therefore contribute less sediment to the Louisiana coast; future planning efforts should consider these probable effects to minimize environmental damages.

Results could be also be applied to assessing sediment budgets and in water quality studies, although additional data and manipulations would be required. Sediment budgets can be assessed by examining changes in concentration and downstream time of travel of the water mass for a number of individual measurements; these can be used to evaluate the supply, transport, and storage of sediment over short scales of time. Water quality assessments for wetland impacts, for consumption, and fish and wildlife issues can also be improved by combining knowledge of the timing of sediment pulses of the silt-clay fractions with available data regarding sediment-associated chemicals.

<u>Recommended future work</u>

In addition to some of the recommendations described above, examination of other factors in the Mississippi-Atchafalaya system may enhance understanding of discharge-sediment relationships, including detailed assessments of velocity, width, depth, turbulence, and temperature, and should be studied in future investigations. Velocities and temperature are the most readily available, width and depth may be computed from raw data which are less readily available, although few detailed measurements of turbulence with sediment transport have been made.

Velocity, width, and sediment load are typically larger and depth is smaller on the rising limb than for similar discharges on the falling limb (Leopold et al., 1953; Leopold et al., 1964). Although discharge incorporates these three parameters, it is possible that the correlations could be improved if they were examined individually. Turbulent fluctuations of stream velocity, which can vary 20% above or below the mean in as little as 15 minutes, and are accompanied by local eddying, can cause short-term variations in suspended sediment concentration, particularly of the coarser material, in the Mississippi River (Schoellhammer and Curwick, 1985).

The relationships of sediment transport and temperature are complex and poorly understood in large rivers. Thus, it is no surprise that Robbins (1977) did not detect differences between sediment transport and temperature on the Mississippi at Arkansas City and Natchez. Studies in much shallow rivers, as on the Colorado (Lane et al., 1949), Niobrara (Colby et al., 1965), and in the laboratory (Franco, 1968), have shown that sediment transport often increases with decreasing water temperature, since both the water density and the water's kinematic viscosity are dependent upon the temperature (Graf, 1971). Changes in viscosity affect the thickness of the laminar sublayer, which can affect both bed material movement and the bedforms, and the settling velocity of particles. The effects of temperature are stronger for grain diameters less than 0.5 mm (medium sand) because the settling velocities of finer particles are most affected by Stokes law (Colby et al., 1965; Walling, 1974).

In temperate and colder climates, however, the opposite relationships may occur such that lower concentrations are typical of colder, snowmelt-generated floods compared to higher concentrations in warmer runoff-generated floods which erode more as they move at higher velocities (e.g. Richards, 1984). Both snowmelt and runoff events are prominent in the Mississippi-Atchafalaya system, and though it would be difficult to separate these in a large basin, further work in the study area and other large rivers concerning these differences is recommended.

Further interpretation of the climatic and seasonal differences in the study area may also improve understanding of discharge-suspended sediment relationships. The summer with accompanying dry and dusty surface conditions provides a greater availability of sediment and further, the increased occurrence of intense convectional rainfall which possesses a high erosive capacity (Walling, 1974) result in high erosion rates (Guy, 1964).

Modes of sediment supply, including resuspension, tributary contributions, and bank failures also require more detailed studies. Resuspension and settling are important processes in the Mississippi-Atchafalaya river system, as shown at Belle Chasse, which probably derives much of its silt-clay concentration during high discharges from resuspension of bed material. Several examples have shown how tributary contributions may cause peaks. In addition, there may be a number of peaks of substantial magnitude related to sources where data were not available or were not collected. Bank failures, while not as significant as years past (Winkley, 1977), may still be important for sediment supply on the Atchafalaya and Red rivers, where much of the channel is not revetted. Testing whether sediment peaks are in fact due to resuspension, tributaries, or bank inputs would require detailed size, mineralogical, and chemical characterizations of the input material and material in transport. Furthermore, determination of whether the amount of sediment removed from the bed, transported in the tributaries, or liberated from the banks is sufficient to account for the transport in the peaks is also required.

Related efforts might consider the application of nonlinear functions to help improve the accuracy of discharge-suspended sediment relationships and the annual loadings which are presently computed using linear functions. This might not be required in the Red River, where the model forms are linear, but might reduce various sources of error on the Mississippi, particularly when sampling is relatively infrequent.

Detailed investigation of discharge-sediment relationships upstream in tributaries and in the main channel is recommended. Historical accounts of other types of available data, field work, and remote sensing may provide a better understanding of bank failures, and contributions from human disturbances such as dredging and construction activities. Process-response relationships could be better understood if different types of floods, from a climatic, hydrologic, geometric, or statistical perspective were examined and categorized. If categorized and separated accordin to their causal phenomena, such as tributary contributions, bank failures, and various types of human activities, sediment peaks and thresholds on time series may be better understood. The use of the four domains may assist in understanding hysteresis and discharge-suspended sediment relationships in this system and other large rivers.

CONCLUSIONS

1. The Mississippi-Atchafalaya River system shows spatial and temporal variations in discharge-suspended sediment relationships. The spatial variations between the Mississippi and the Red are due largely to differences in basin climate, vegetation, geology, and human activities. The variations in the Old and Atchafalaya rivers can be largely explained by their sources. The temporal variations include nonstationarity, or declining trends in mean concentration on the Mississippi, Red, and the rivers that they feed. The Mississippi-fed rivers also show serial dependence.

2. In many years, the Red River constitutes the dominant source of sediment for the Atchafalaya or has a very pronounced influence on its sediment signature, even though in all years its discharge was less than that contributed through Old River. Analysis of discharge-suspended sediment relationships in the Atchafalaya therefore require detailed evaluation of the Red River.

3. Empirical relationships of suspended sediment concentration, and its dominant component the silt-clay concentration, with discharge show nonlinearity. The nonlinearity appears to be due to the decreased availability of fine material at high discharges, which in turn may be related to flushing and also reflects the climate and human activities of the basin.

4. Flushing appears to be a major mechanism for sediment transport, but resuspension, tributary contributions, and bank failures need to be evaluated in greater detail. Resuspension appears to be particularly important downstream in the Mississippi, and causes variation in the discharge-suspended sediment relationships from below the diversion to Belle Chasse. Tributary contributions from the Red River to the Atchafalaya are important. Sediment peaks during falling discharges may include bank failures and require more detailed historical documentation.

5. Discharge-suspended sediment relationships in the Mississippi show pronounced hysteresis effects with a lead of sediment peaks before discharge crests. The lead is as much as two months during high discharge years, and decreases with decreasing discharge maxima so that in low discharge years sediment peaks and discharge crests coincide.

6. The occurrence of the timing described above, shows that concepts regarding relationships of basin size and hysteresis effects, and concepts describing the effects of the relative downstream movement of the sediment wave and the floodwave are not locally, and therefore not universally, correct. However, more detailed work is recommended in other large rivers with abundant supply and along the lower Mississippi to examine downstream movement of the waves.

7. The approach of splitting the suspended sediment into fine and coarse components is shown to be useful in that they show different relationships with discharge and may shows downstream variations and therefore can be used to better understand physical processes in the Mississippi-Atchafalaya river system. This approach also may be quite useful for interpreting physical and periodic phenomena in discharge-suspended sediment relationships in other rivers.

8. If relationships between discharge and suspended sediment are nonlinear, as on the Mississippi-Atchafalaya, it may be useful to develop a conceptual diagram spanning different discharge ranges. These may be used to infer whether there might be differences in discharge-suspended sediment relationships between high and low discharge years and what types of differences might be expected.

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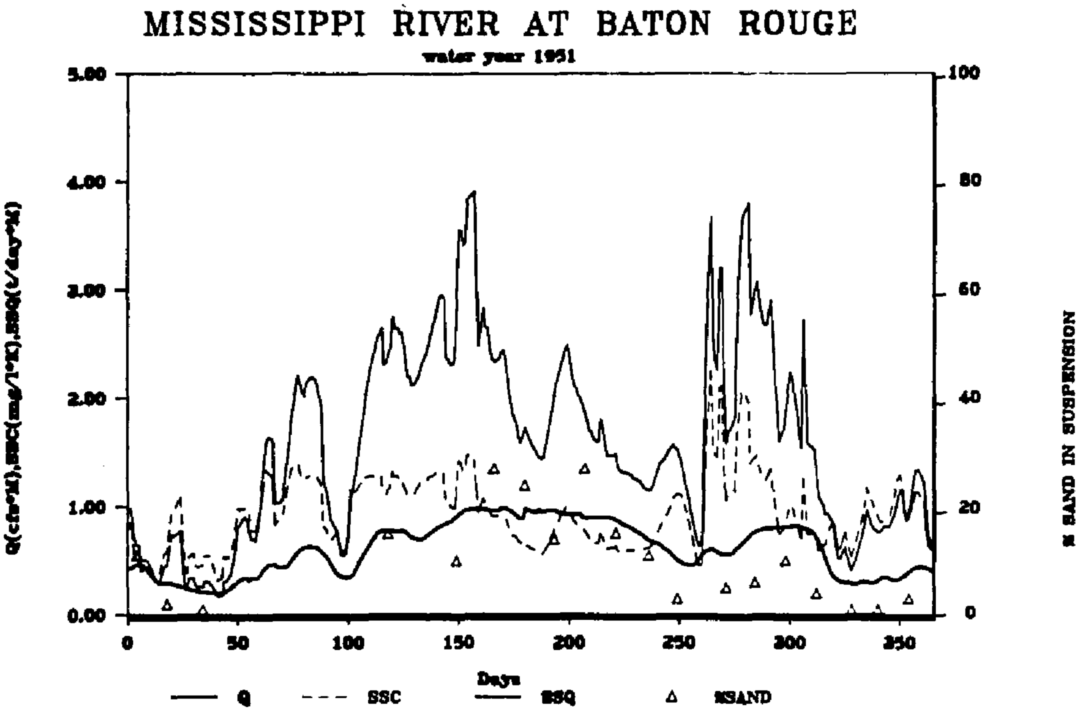
APPENDIX



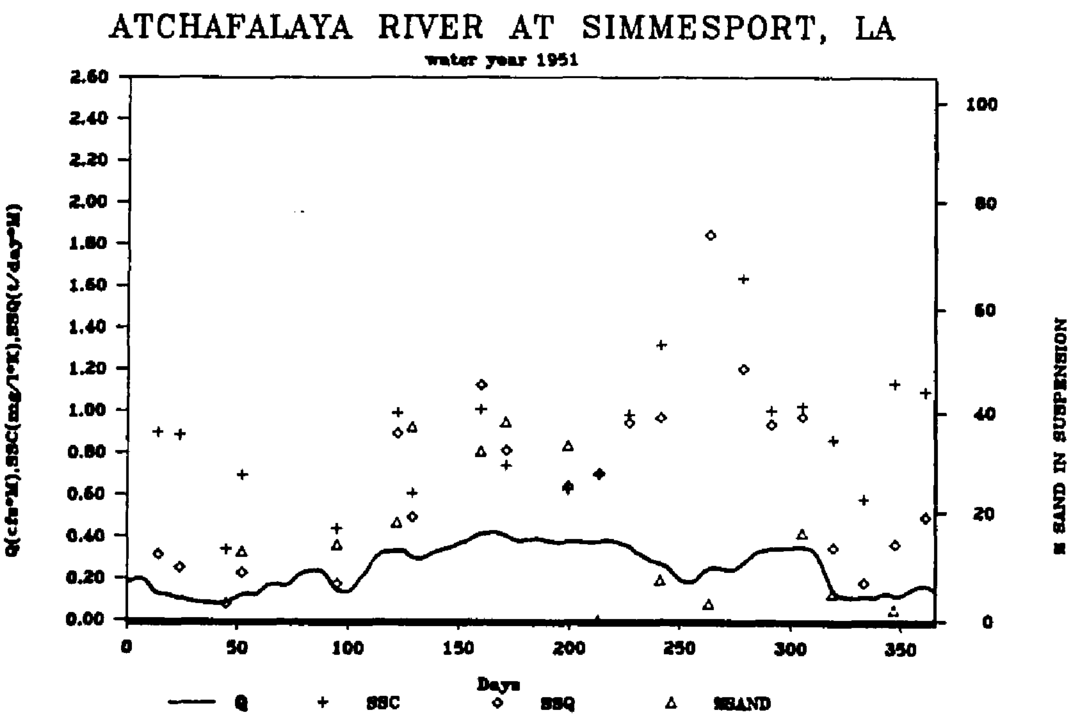


Figure A-1. Discharge-suspended sediment relationships for water year 1951 on the Mississippi-Atchafalaya river system.

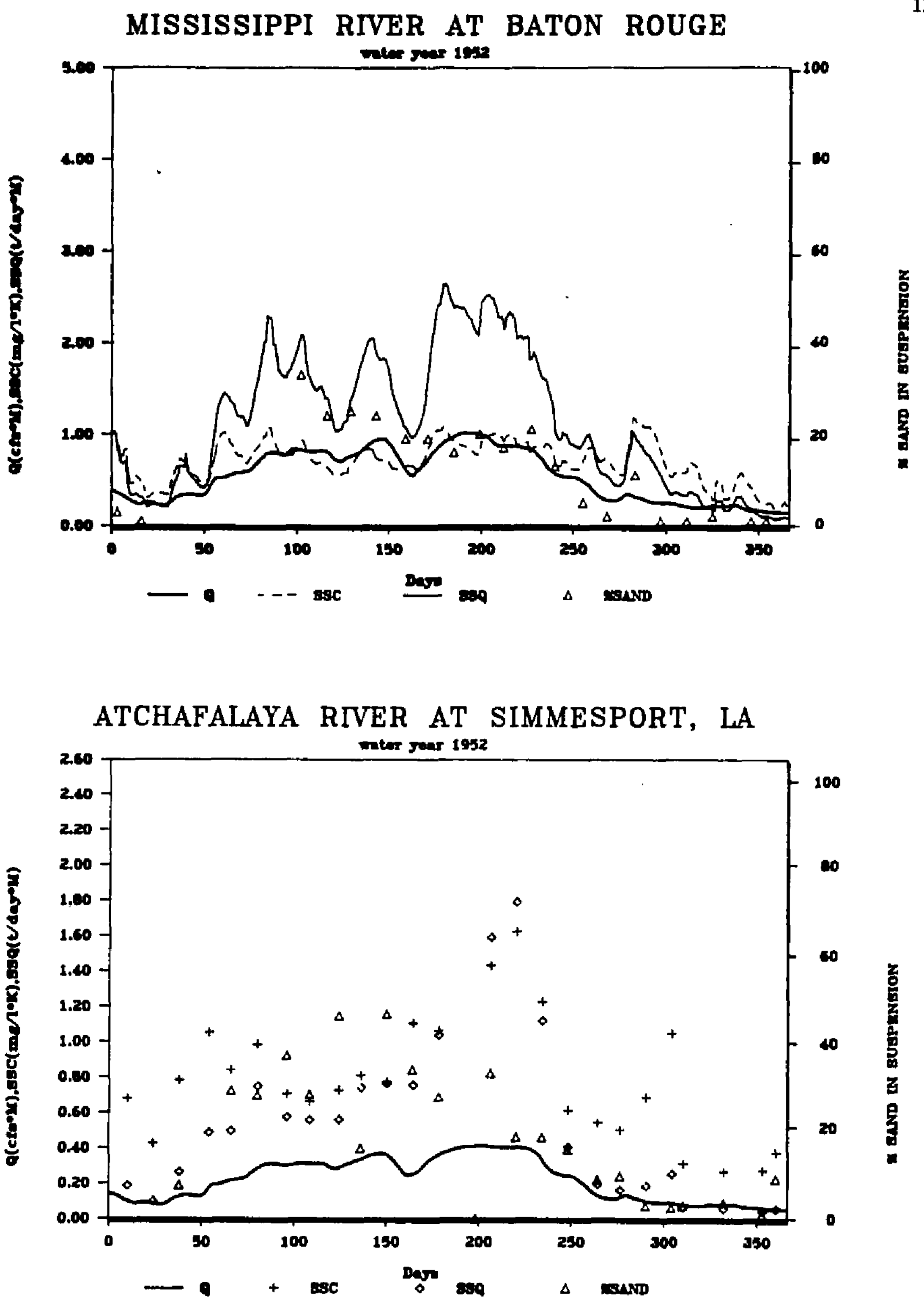
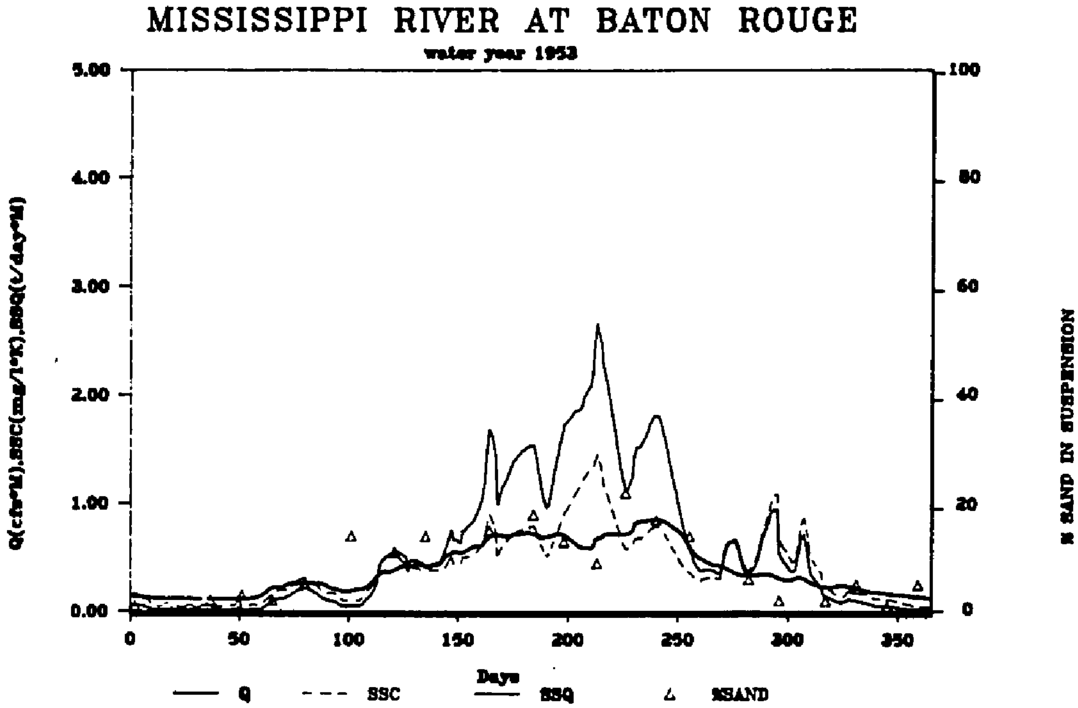


Figure A-2. Discharge-suspended sediment relationships for water year 1952 on the Mississippi-Atchafalaya river system.



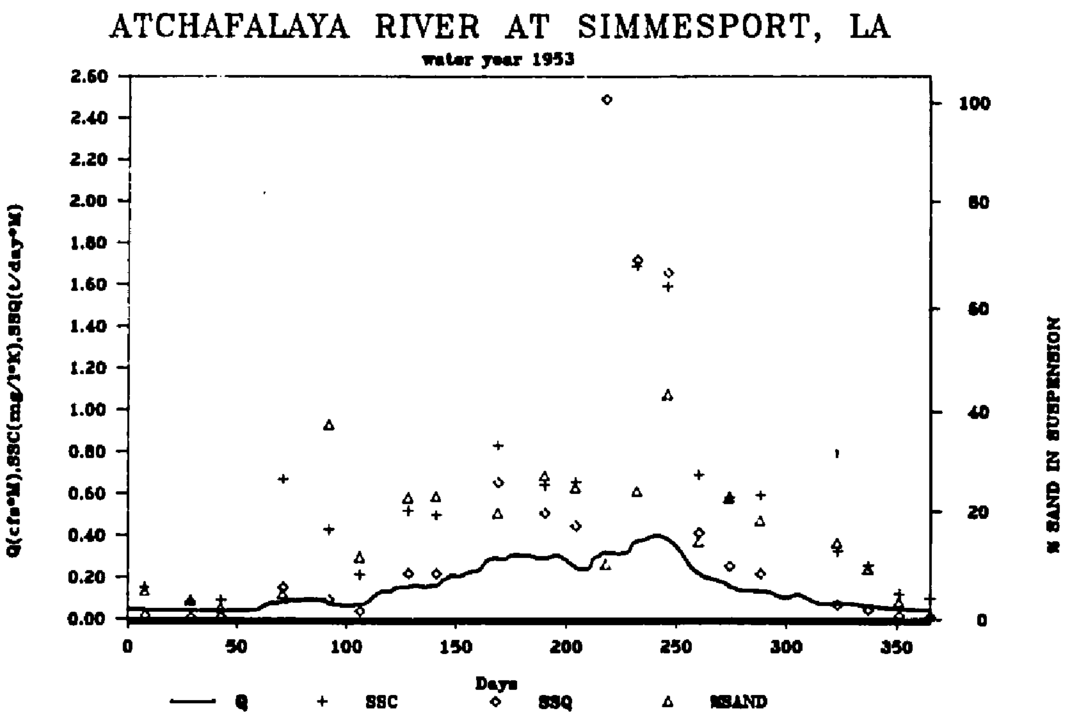


Figure A-3. Discharge-suspended sediment relationships for water year 1953 on the Mississippi-Atchafalaya river system.

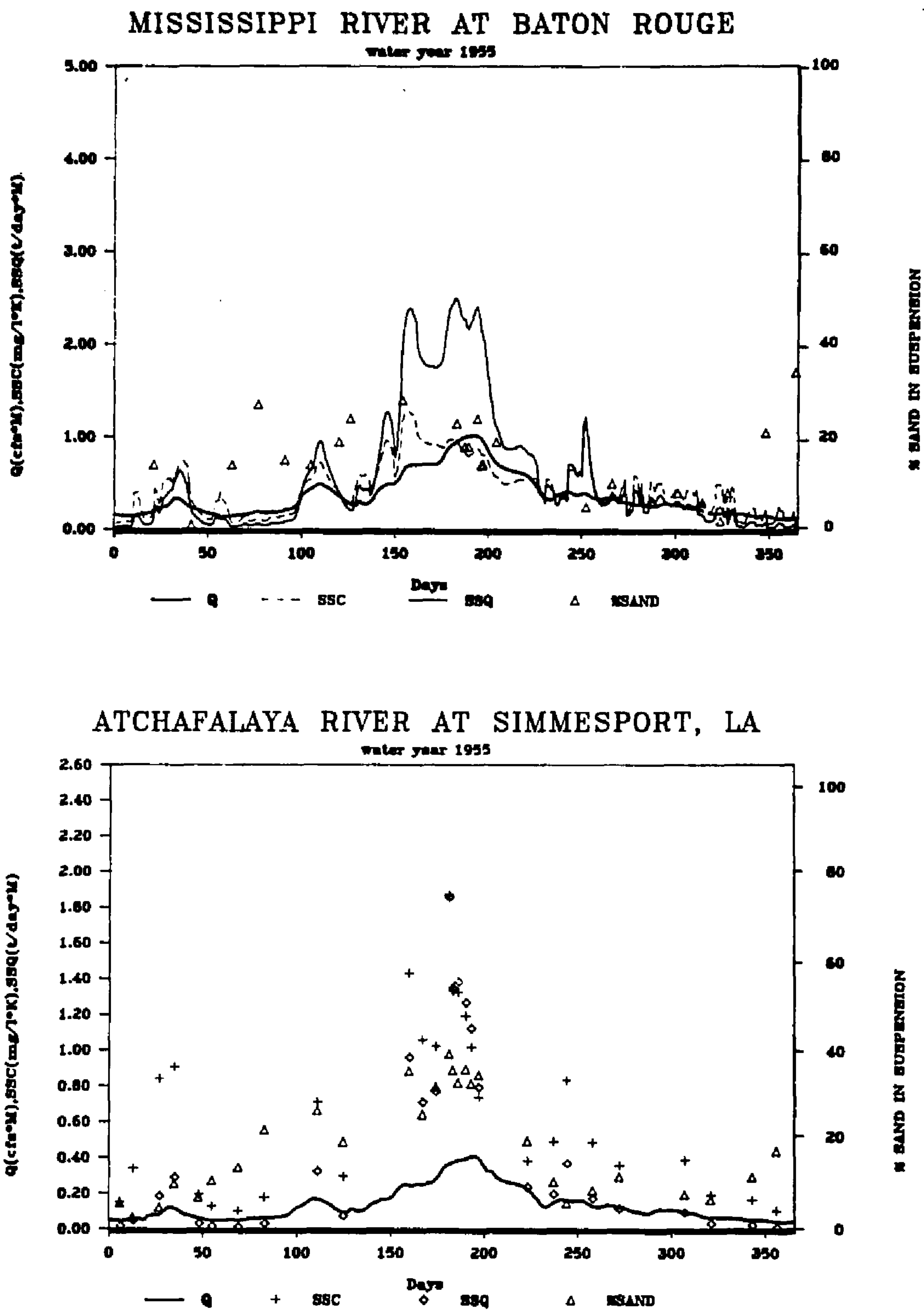
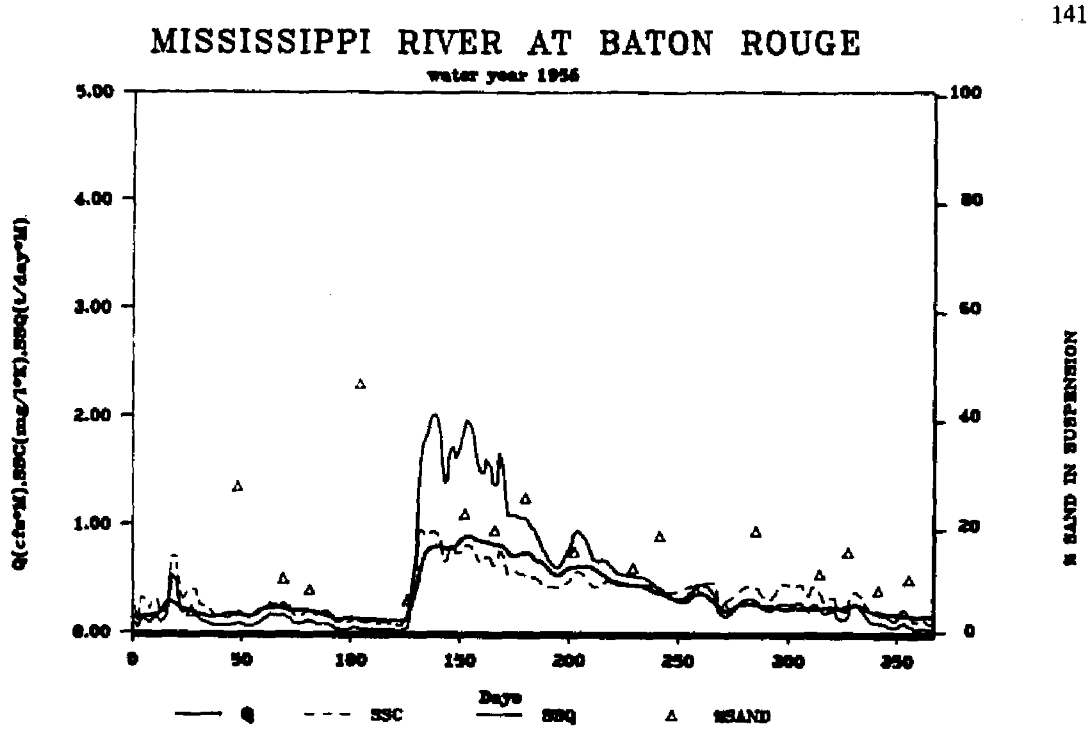


Figure A-4. Discharge-suspended sediment relationships for water year 1955 on the Mississippi-Atchafalaya river system.



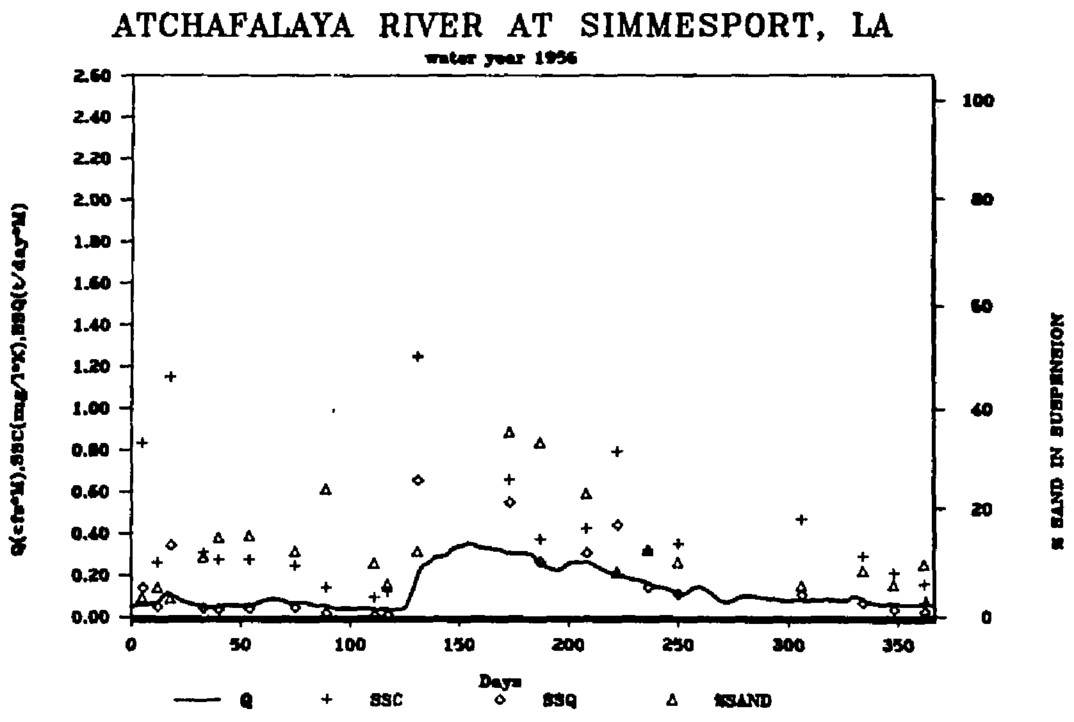
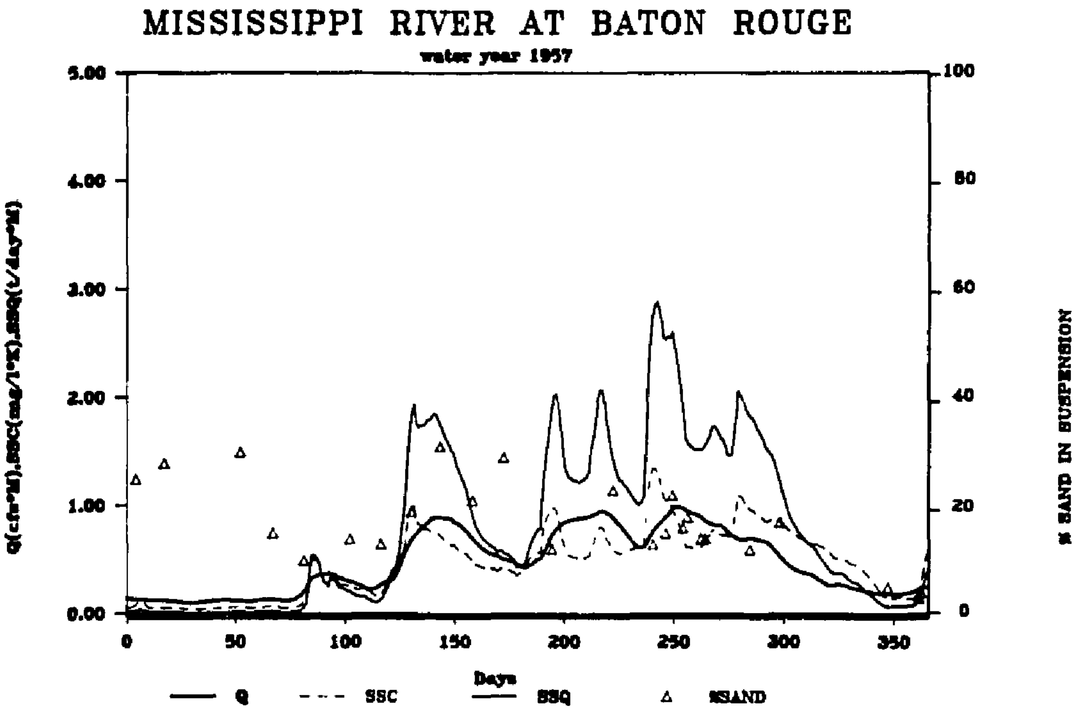


Figure A-5. Discharge-suspended sediment relationships for water year 1956 on the Mississippi-Atchafalaya river system.



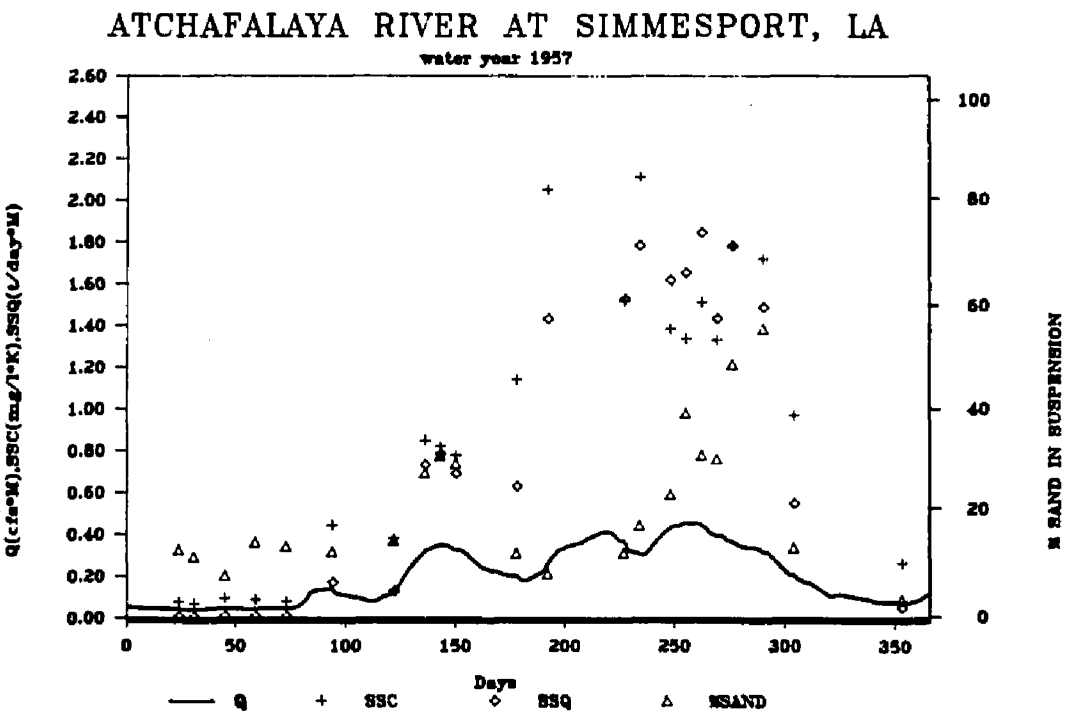
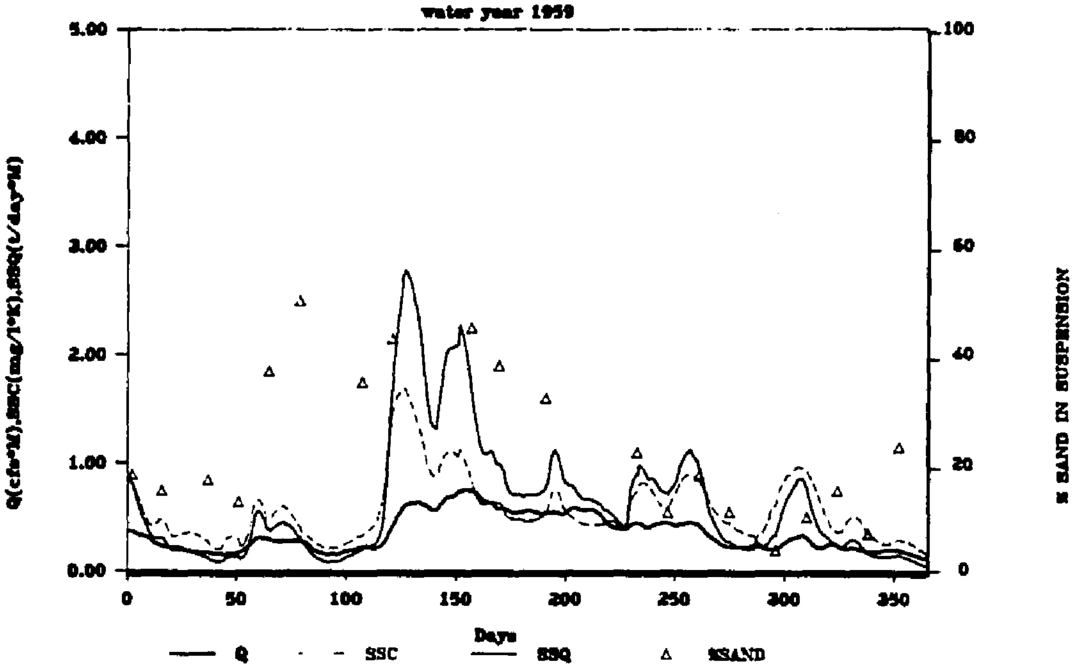


Figure A-6. Discharge-suspended sediment relationships for water year 1957 on the Mississippi-Atchafalaya river system.

MISSISSIPPI RIVER AT RED RIVER LG.



ATCHAFALAYA RIVER AT SIMMESPORT, LA

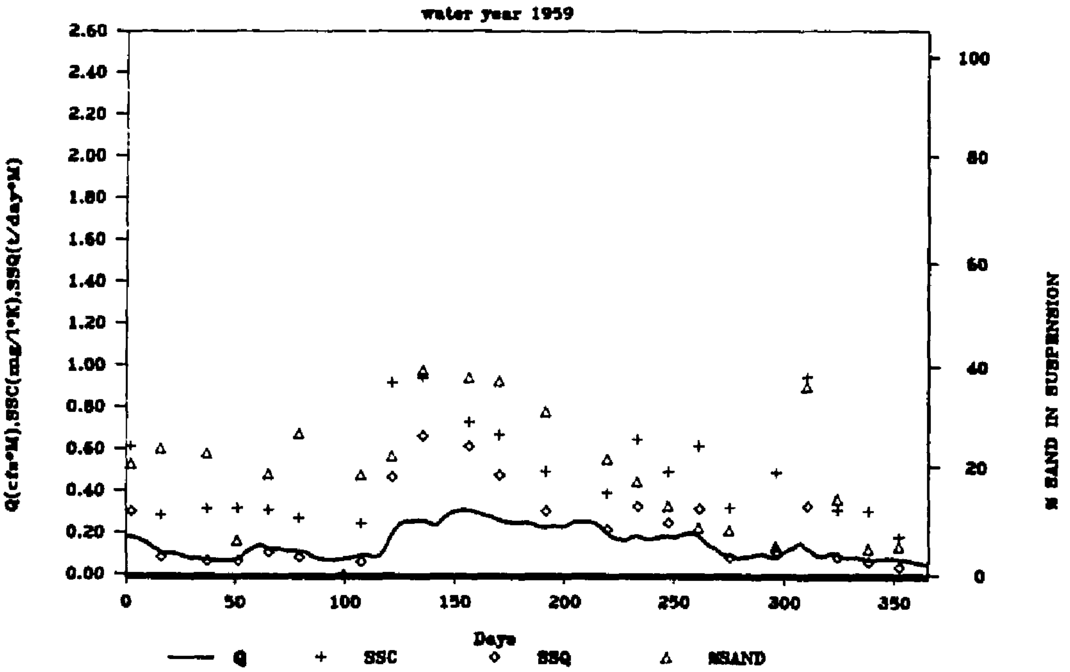
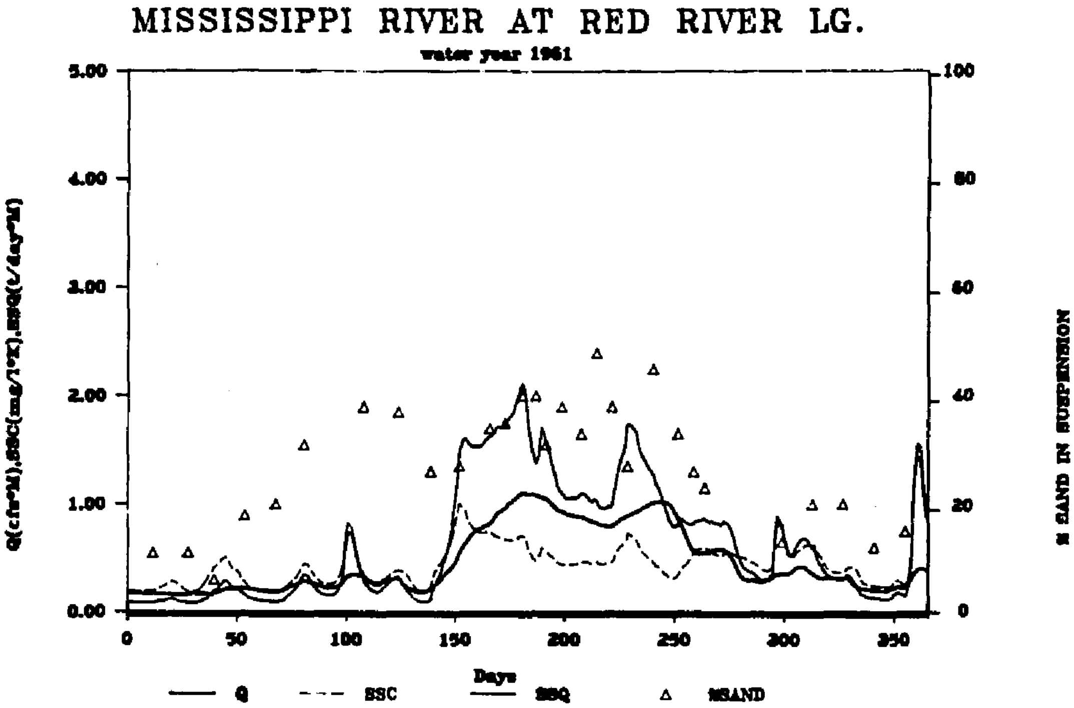


Figure A-7. Discharge-suspended sediment relationships for water year 1959 on the Mississippi-Atchafalaya river system.



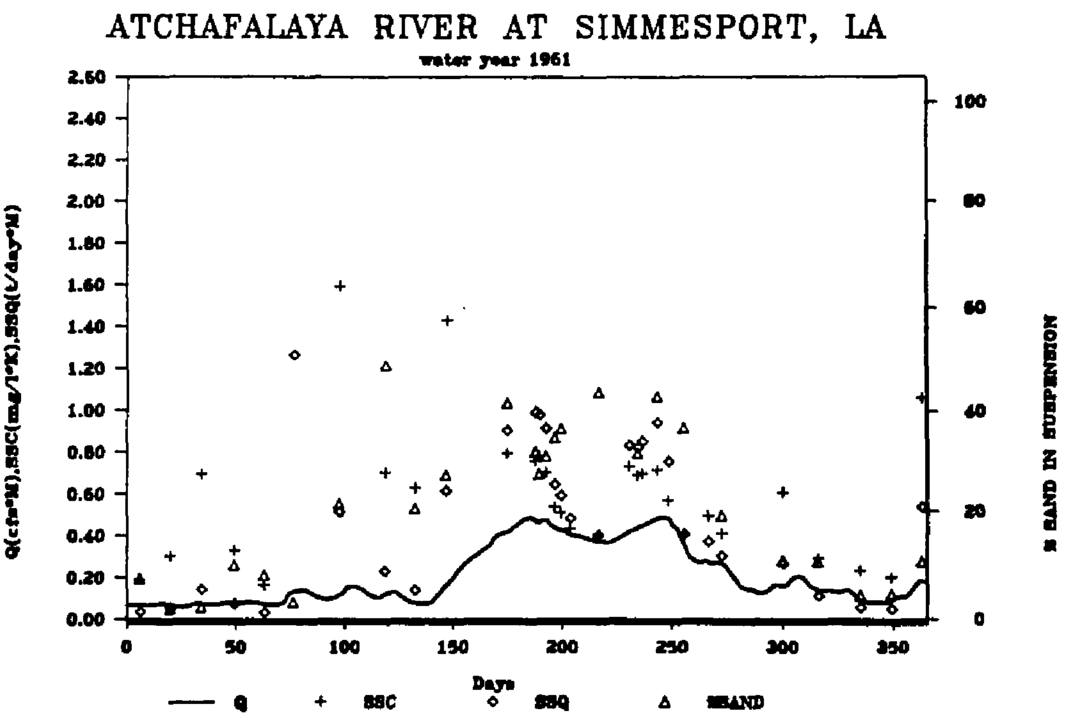
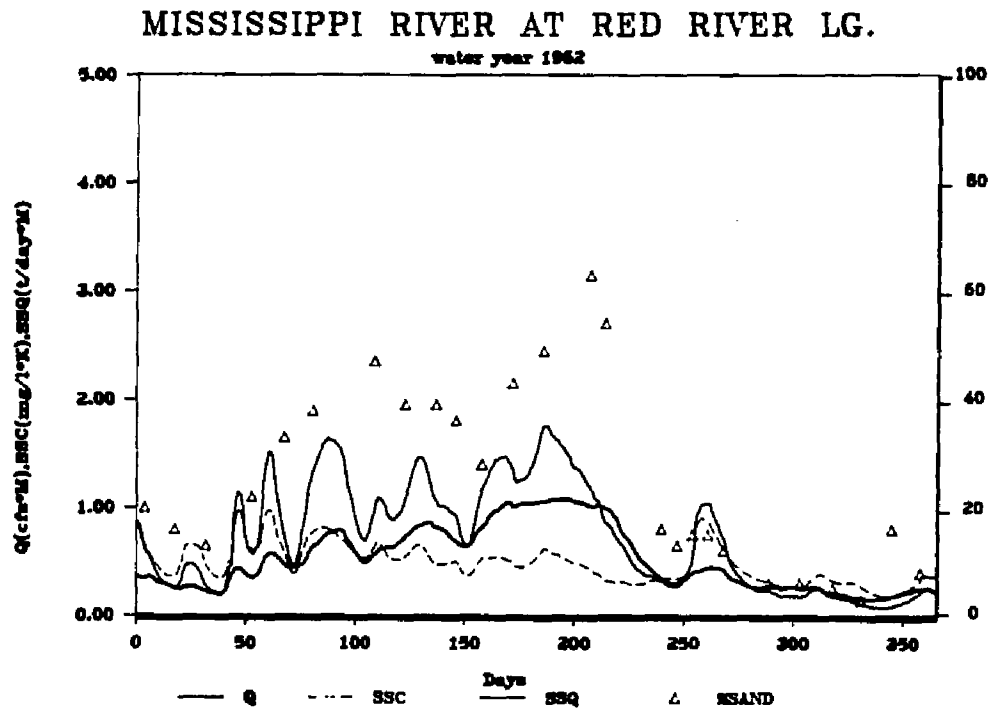


Figure A-8. Discharge-suspended sediment relationships for water year 1961 on the Mississippi-Atchafalaya river system.



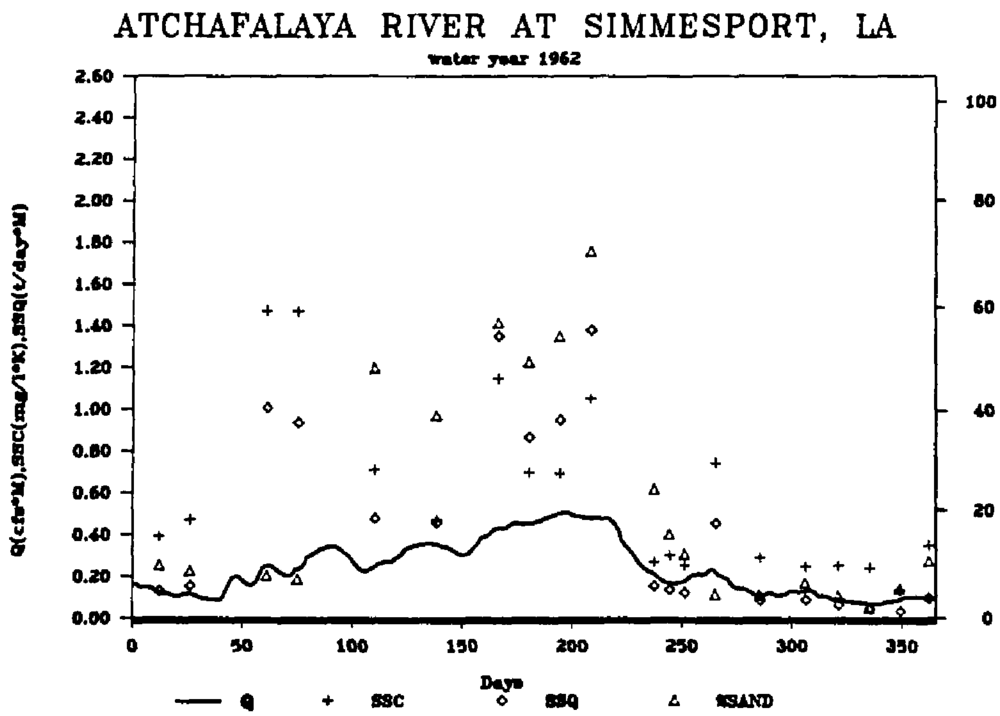
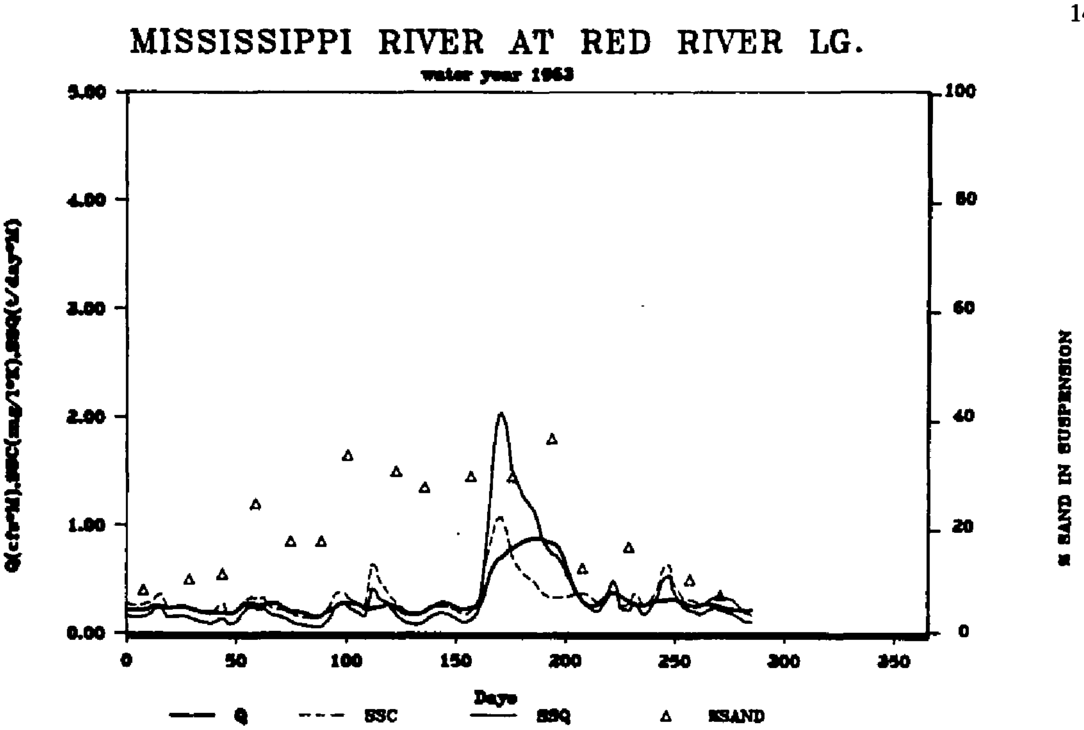


Figure A-9. Discharge-suspended sediment relationships for water year 1962 on the Mississippi-Atchafalaya river system.



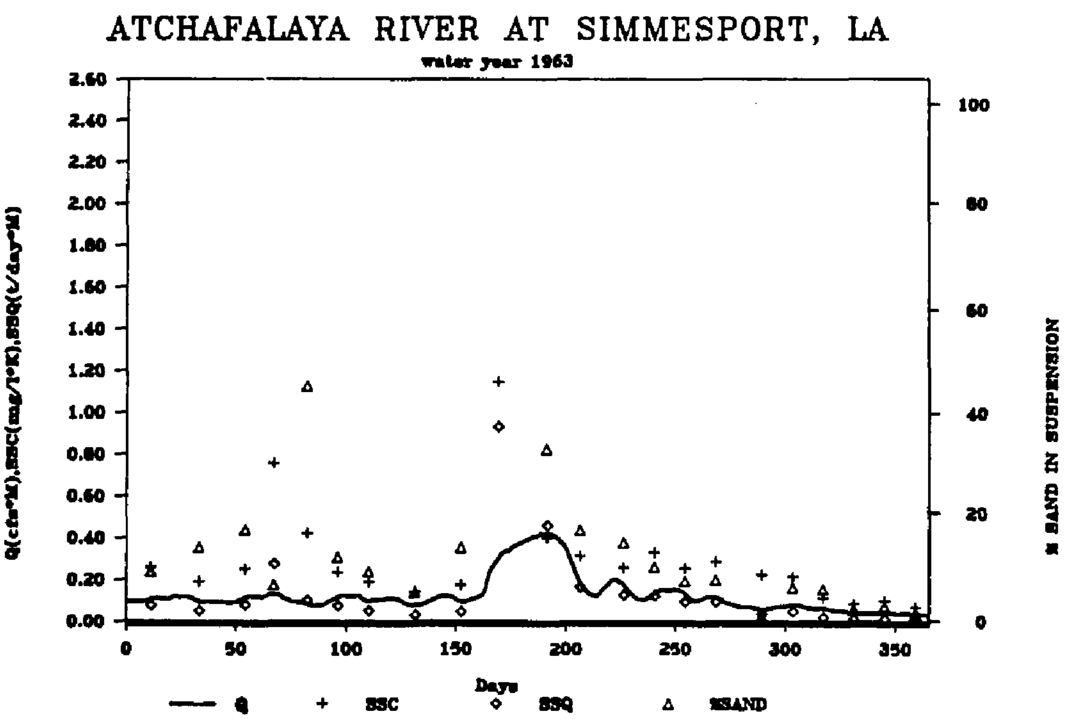
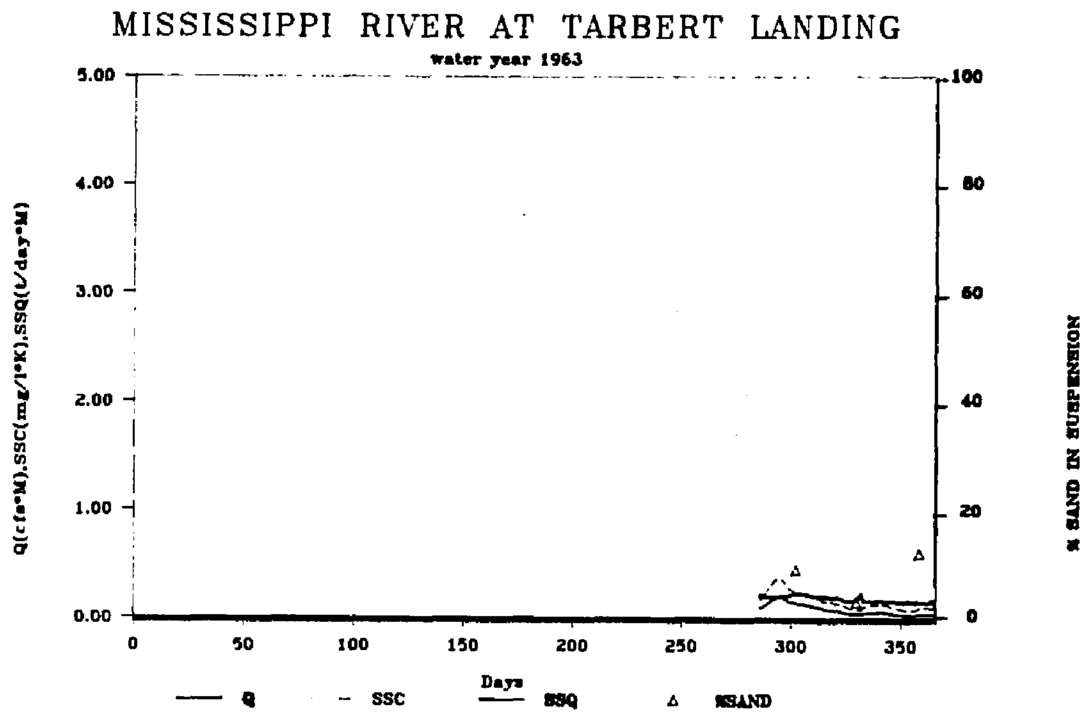


Figure A-10. Discharge-suspended sediment relationships for water year 1963 on the Mississippi-Atchafalaya river system.



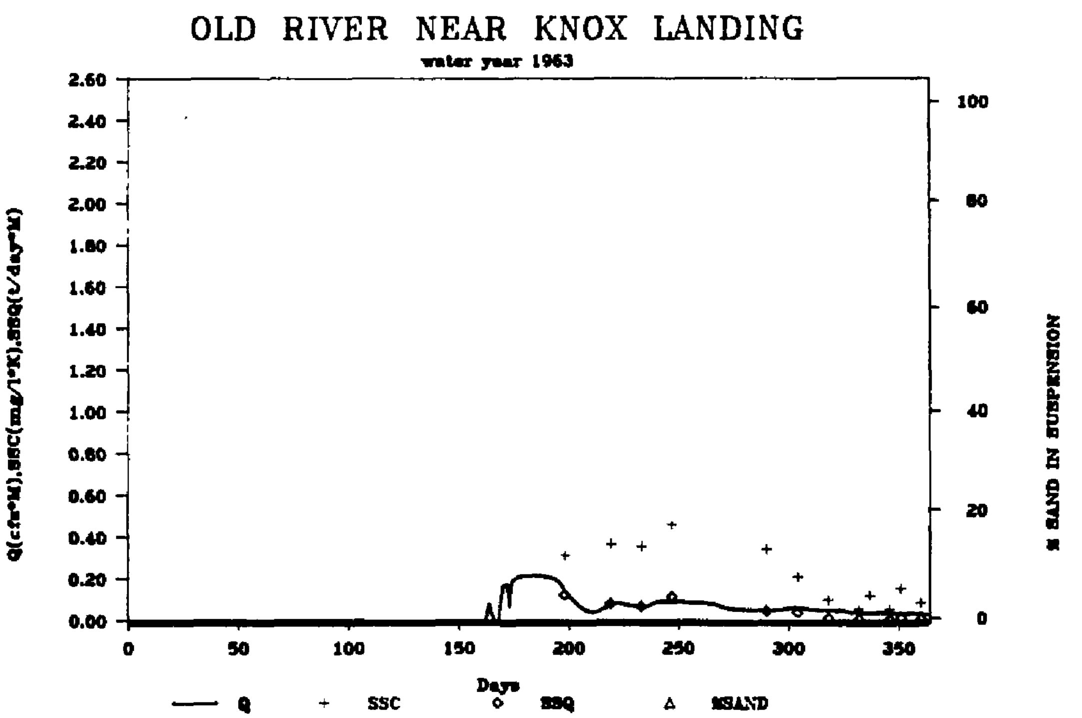
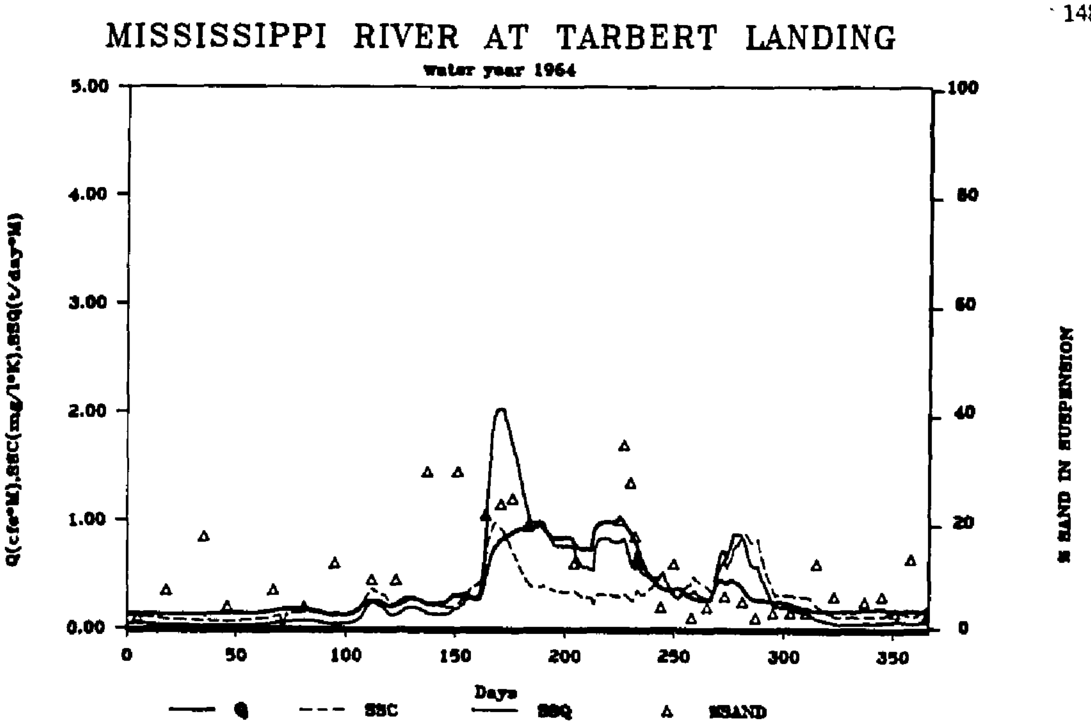


Figure A-10 (cont.). Discharge-suspended sediment relationships for water year 1963 on the Mississippi-Atchafalaya river system.



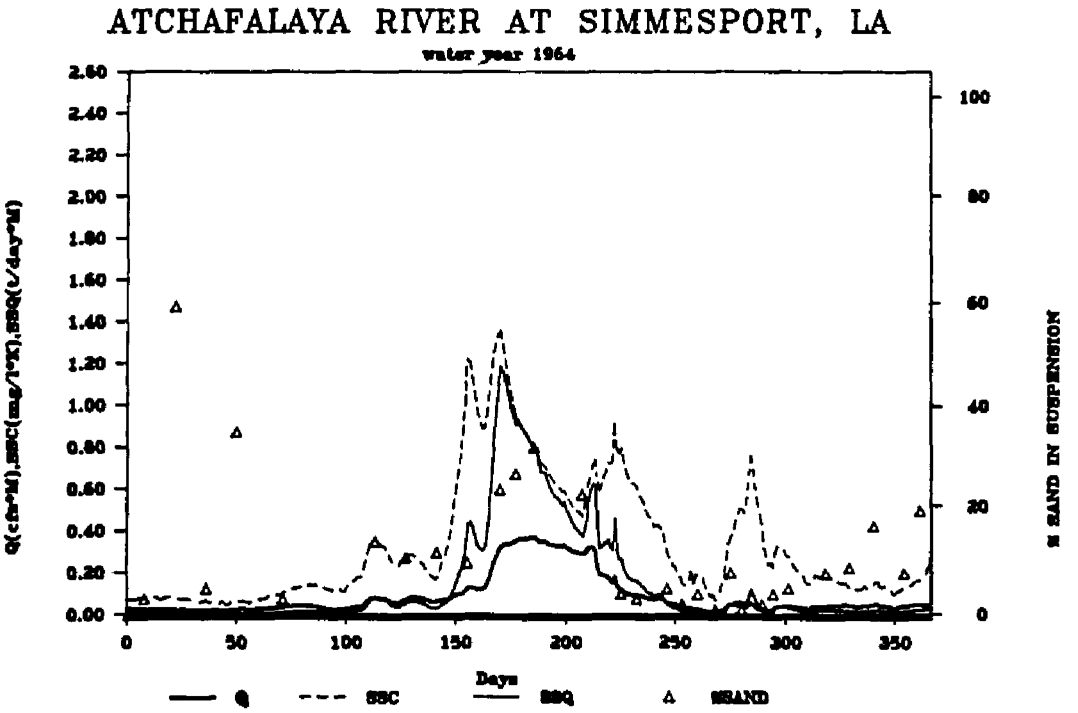
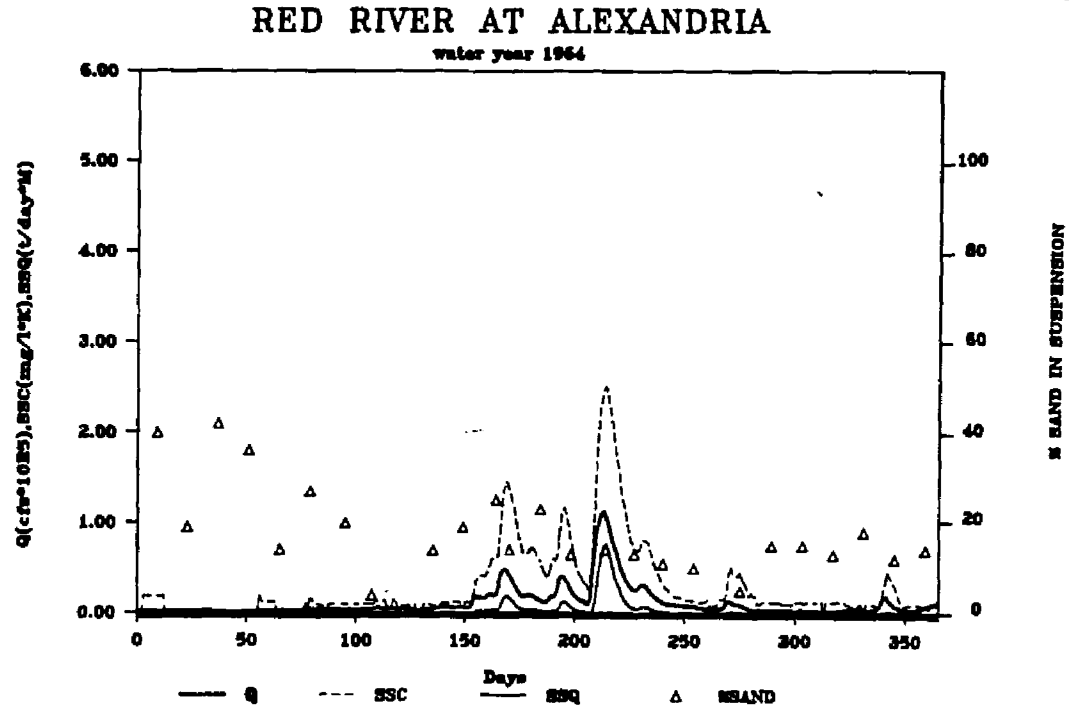


Figure A-11. Discharge-suspended sediment relationships for water year 1964 on the Mississippi-Atchafalaya river system.



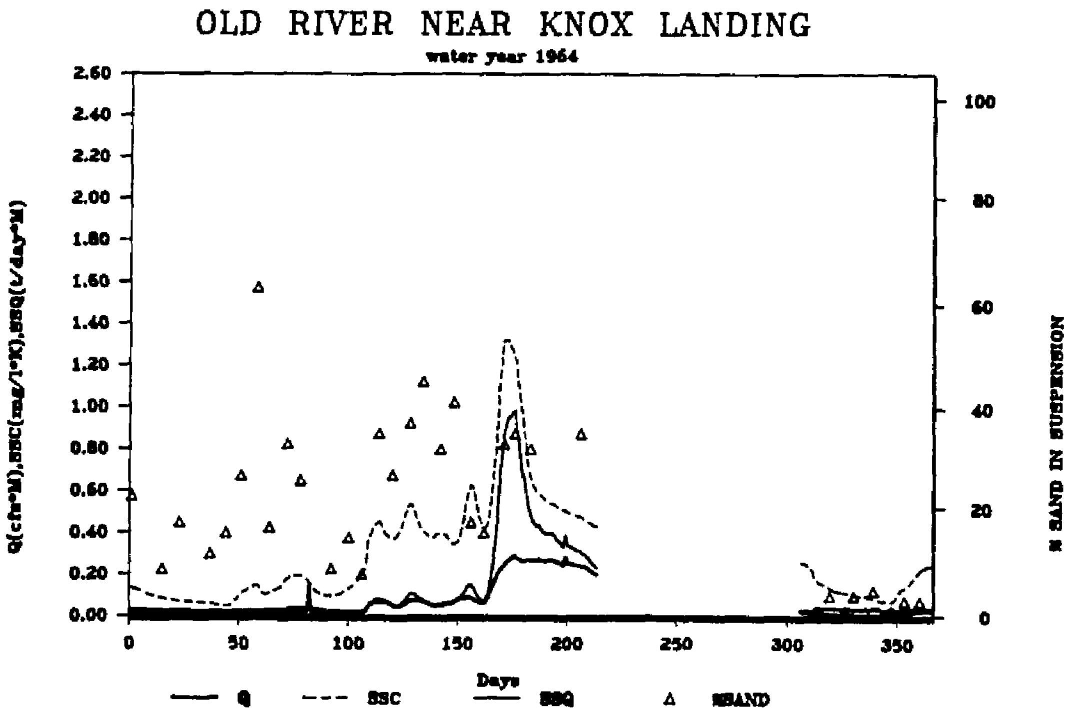
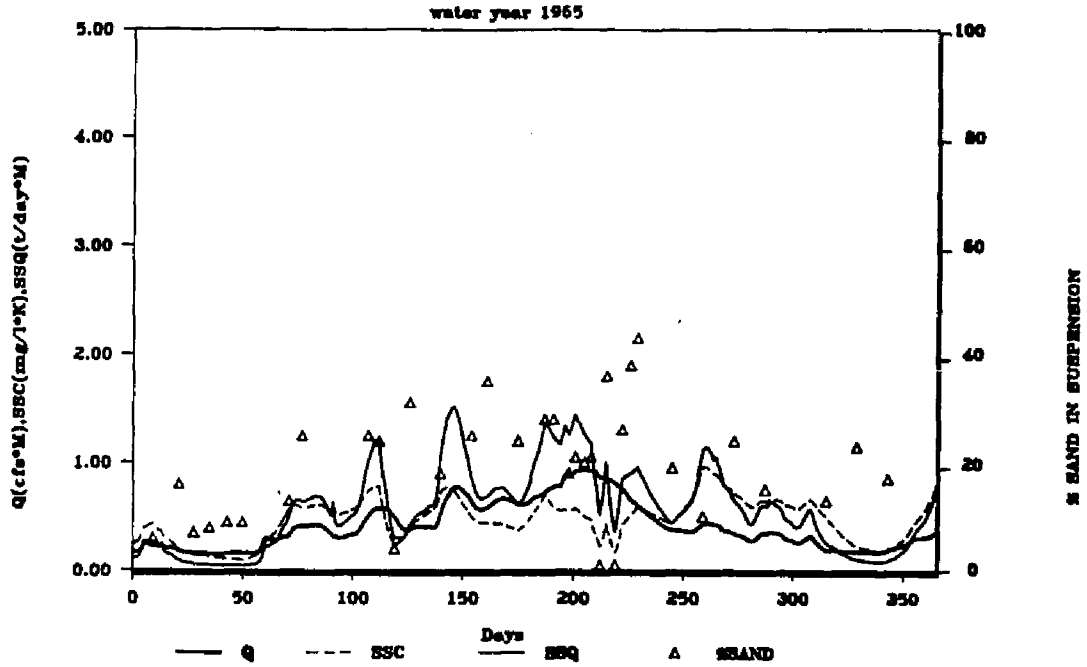


Figure A-11 (cont.). Discharge-suspended sediment relationships for water year 1964 on the Mississippi-Atchafalaya river system.

MISSISSIPPI RIVER AT TARBERT LANDING



ATCHAFALAYA RIVER AT SIMMESPORT, LA

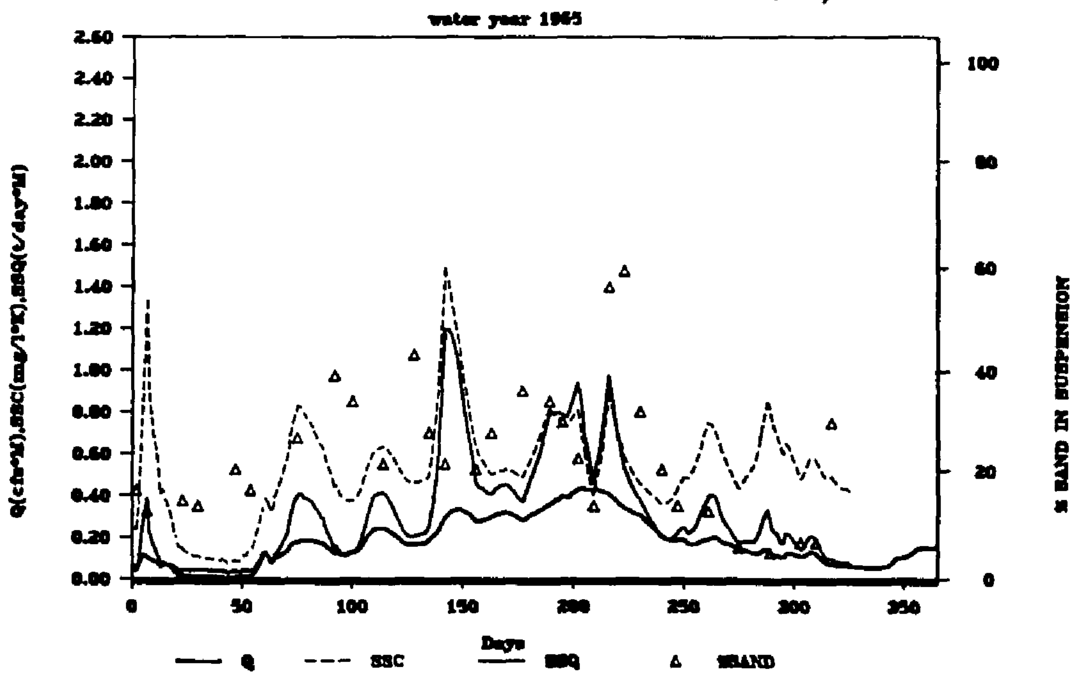
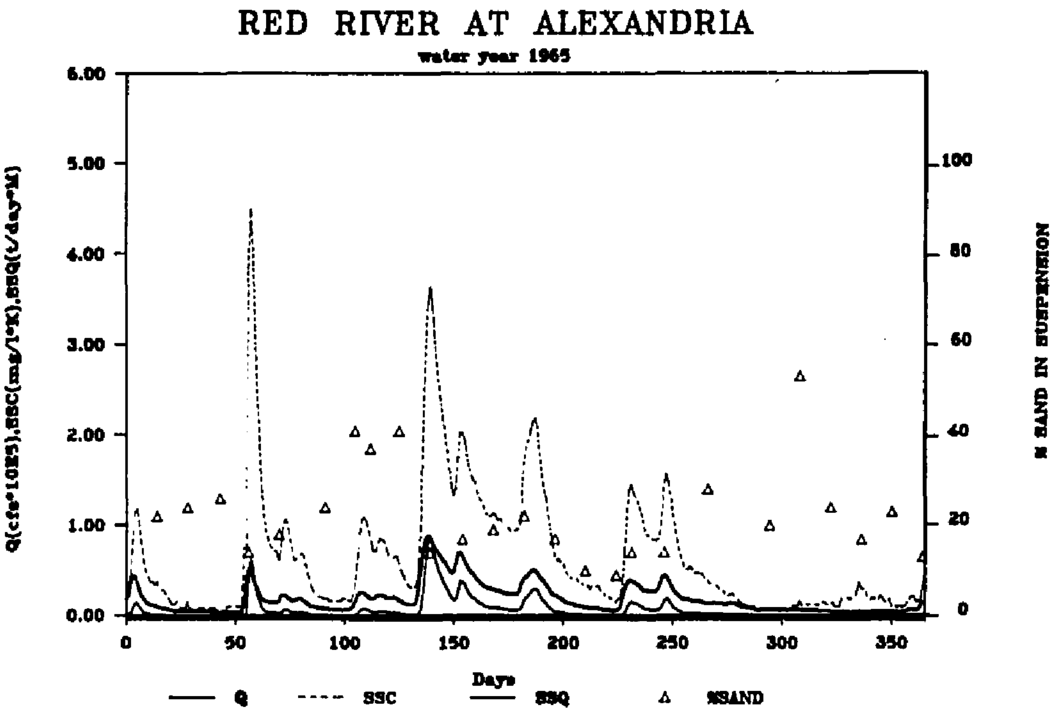


Figure A-12. Discharge-suspended sediment relationships for water year 1965 on the Mississippi-Atchafalaya river system.



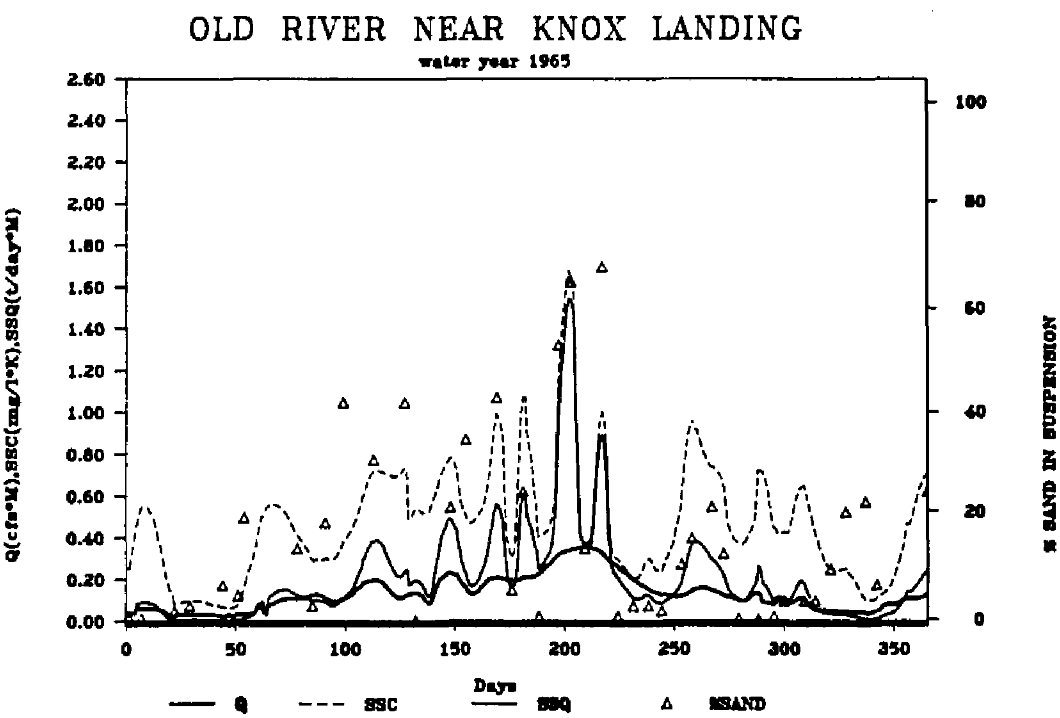
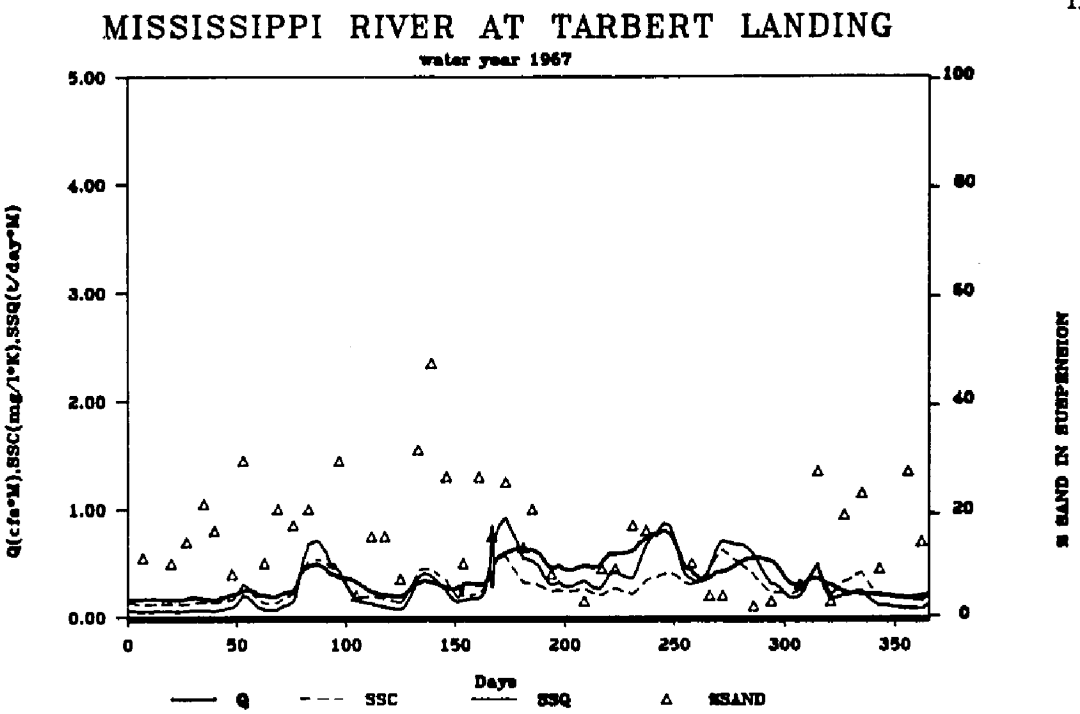


Figure A-12 (cont.). Discharge-suspended sediment relationships for water year 1965 on the Mississippi-Atchafalaya river system.



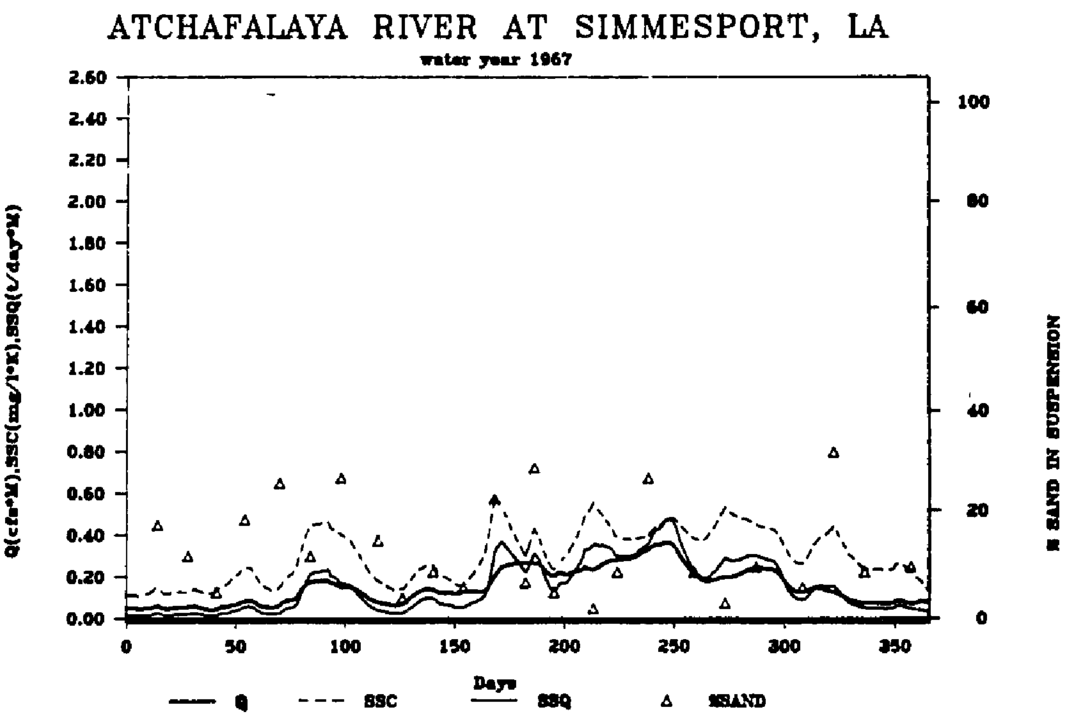
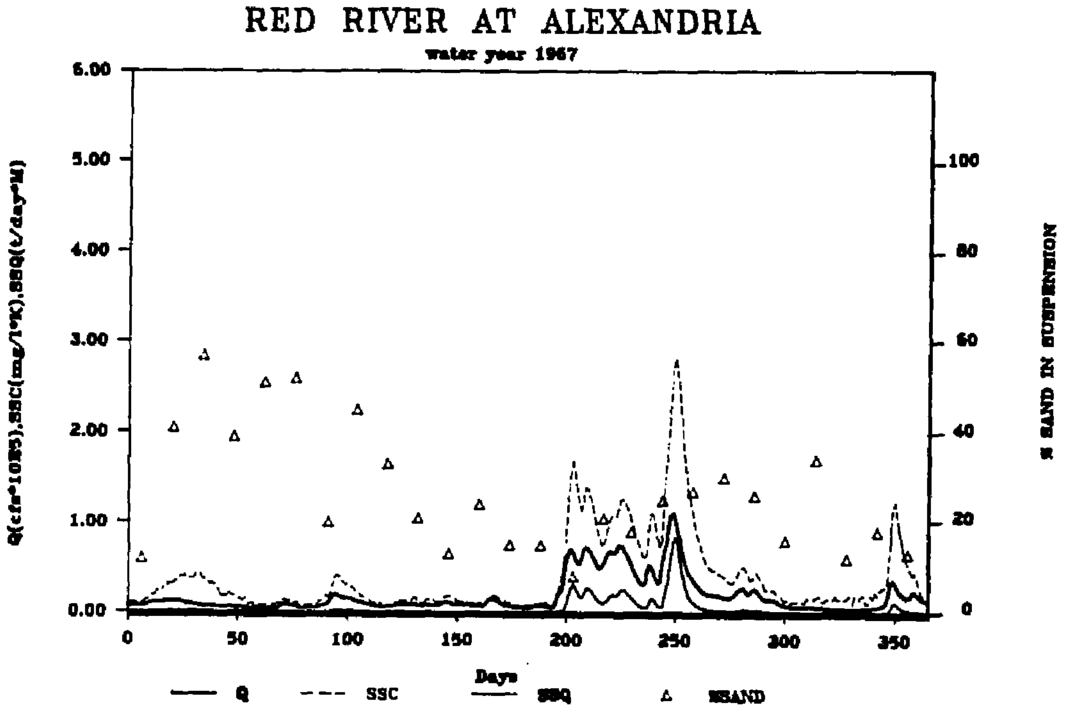


Figure A-13. Discharge-suspended sediment relationships for water year 1967 on the Mississippi-Atchafalaya river system.



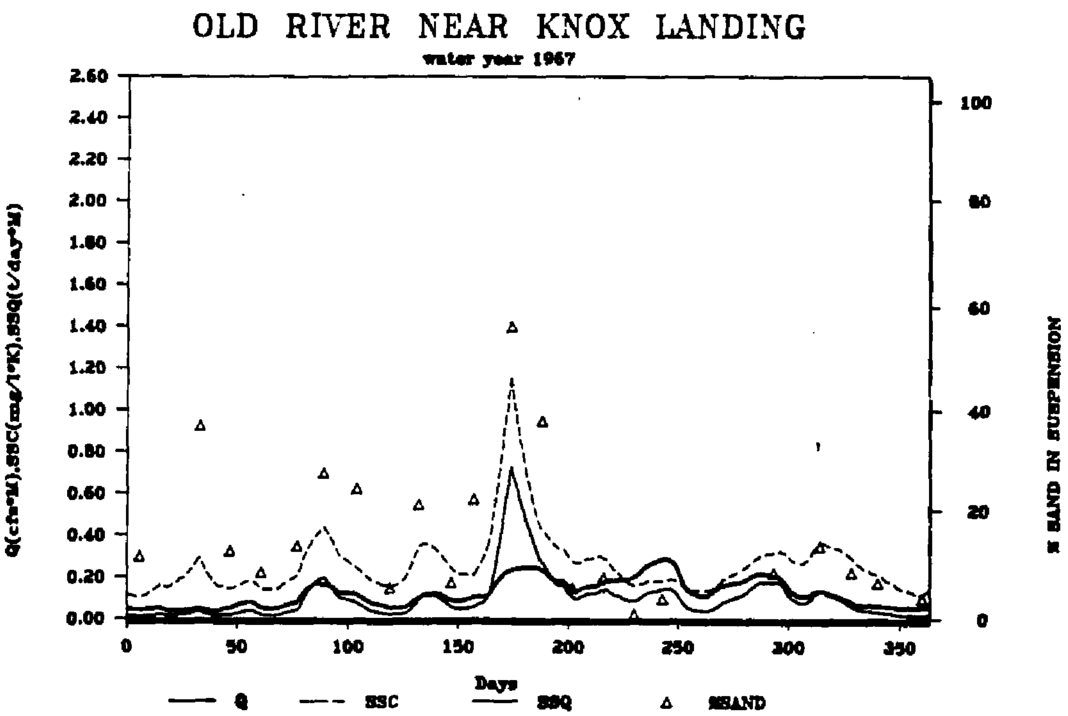
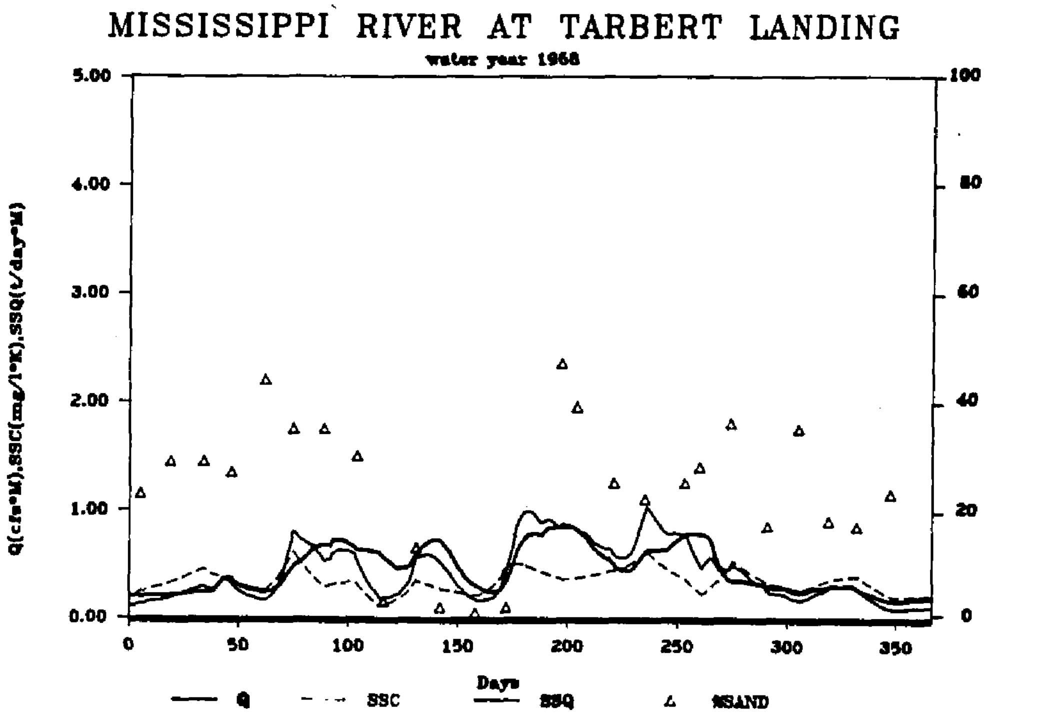


Figure A-13 (cont.). Discharge-suspended sediment relationships for water year 1967 on the Mississippi-Atchafalaya river system.



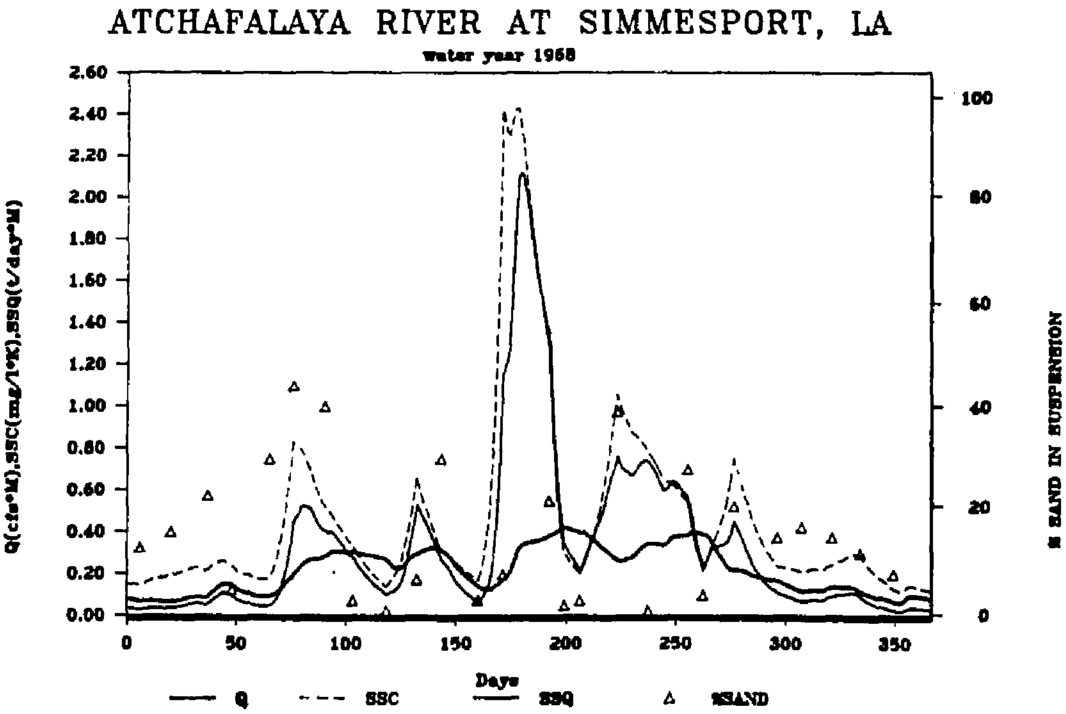
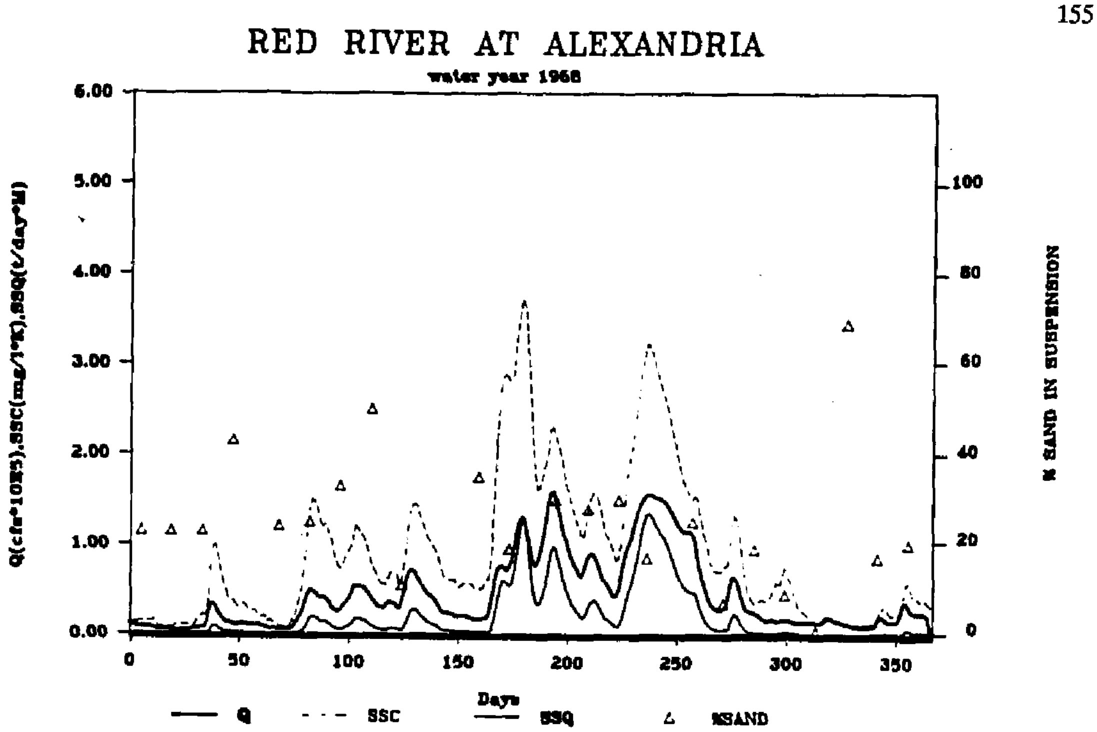


Figure A-14. Discharge-suspended sediment relationships for water year 1968 on the Mississippi-Atchafalaya river system.



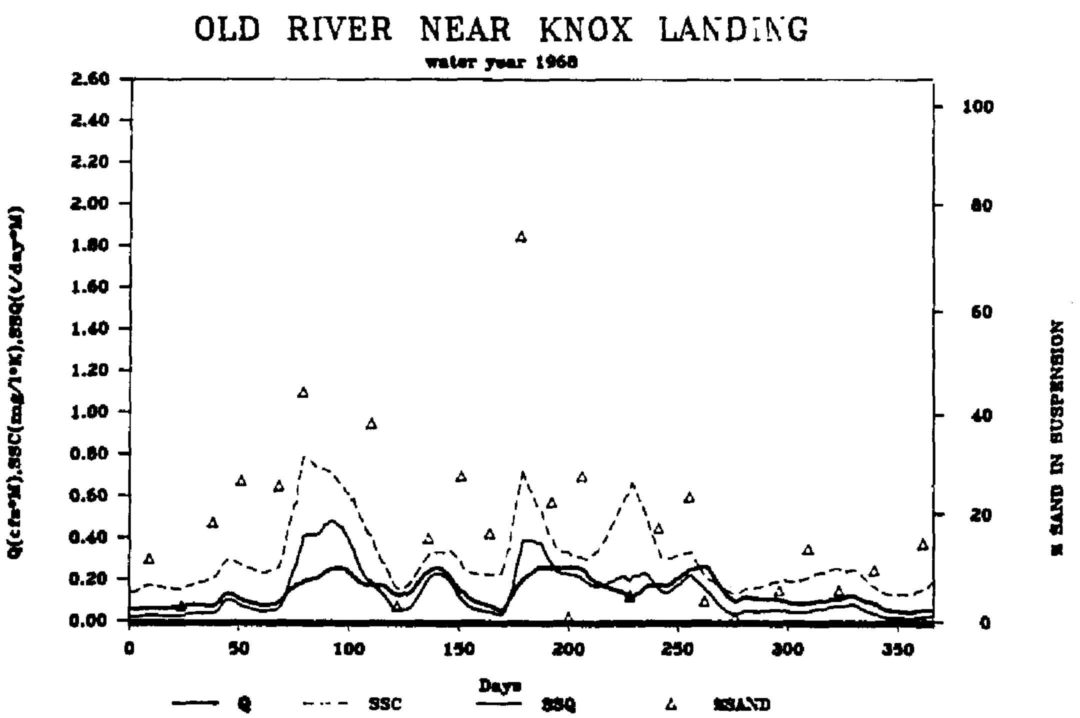
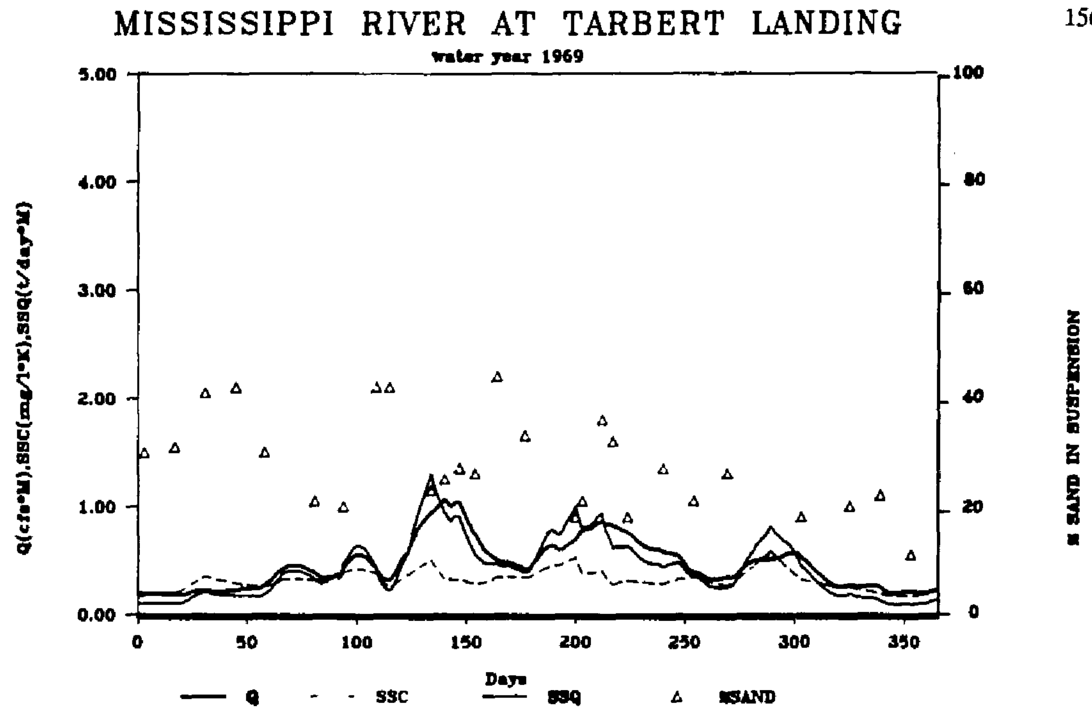


Figure A-14 (cont.). Discharge-suspended sediment relationships for water year 1968 on the Mississippi-Atchafalaya river system.



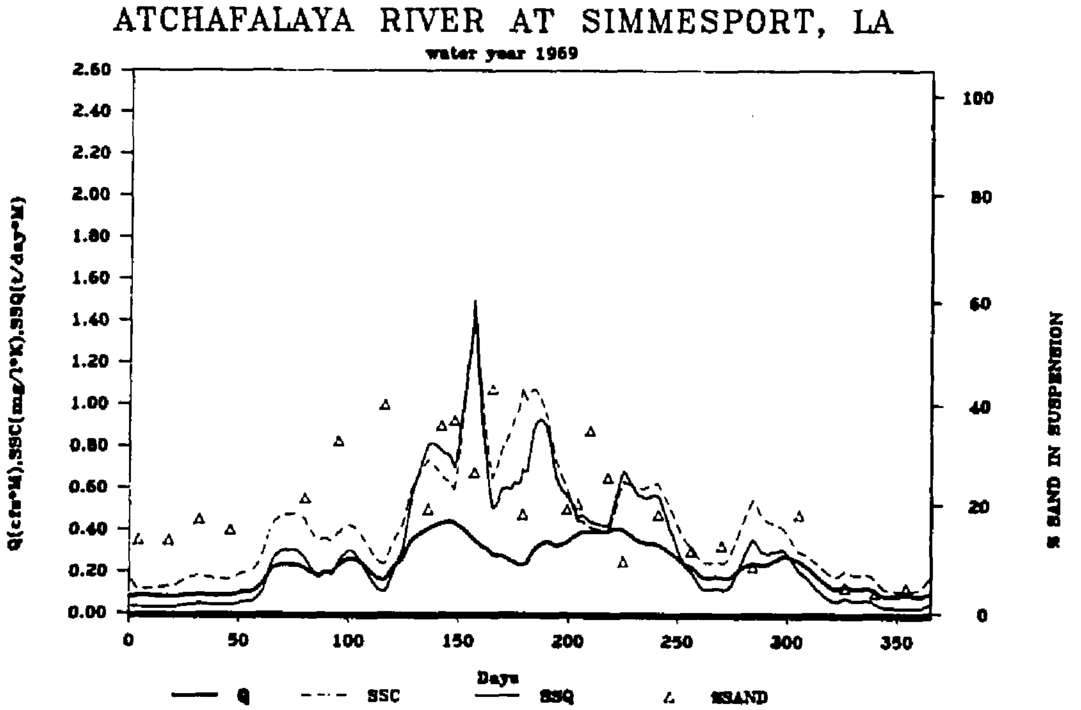
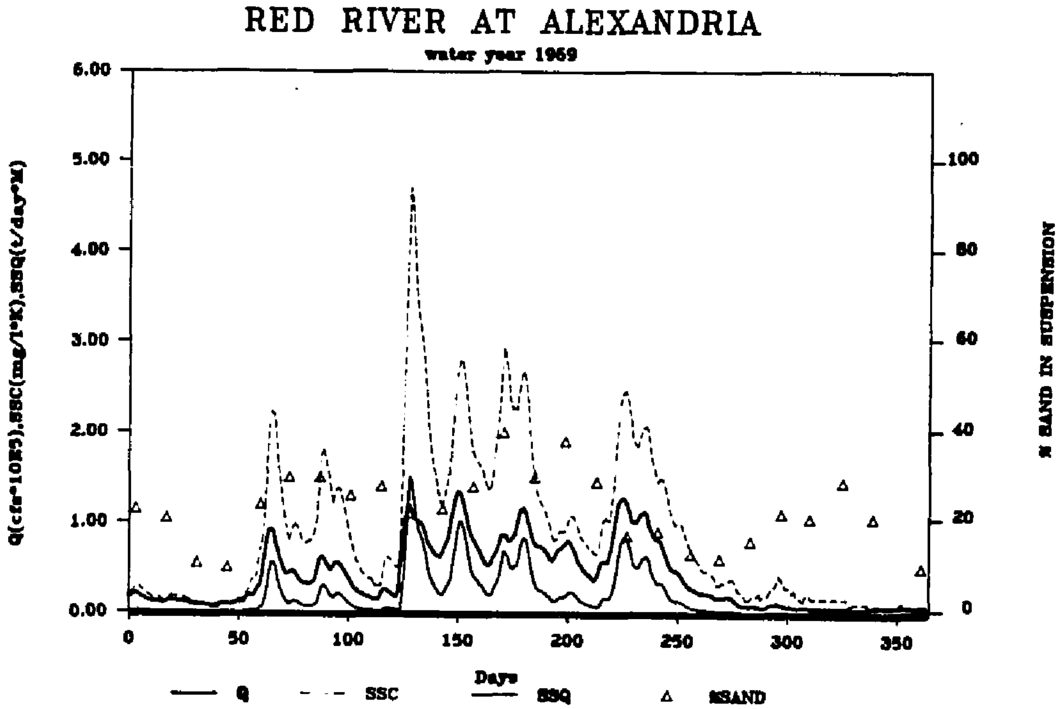


Figure A-15. Discharge-suspended sediment relationships for water year 1969 on the Mississippi-Atchafalaya river system.



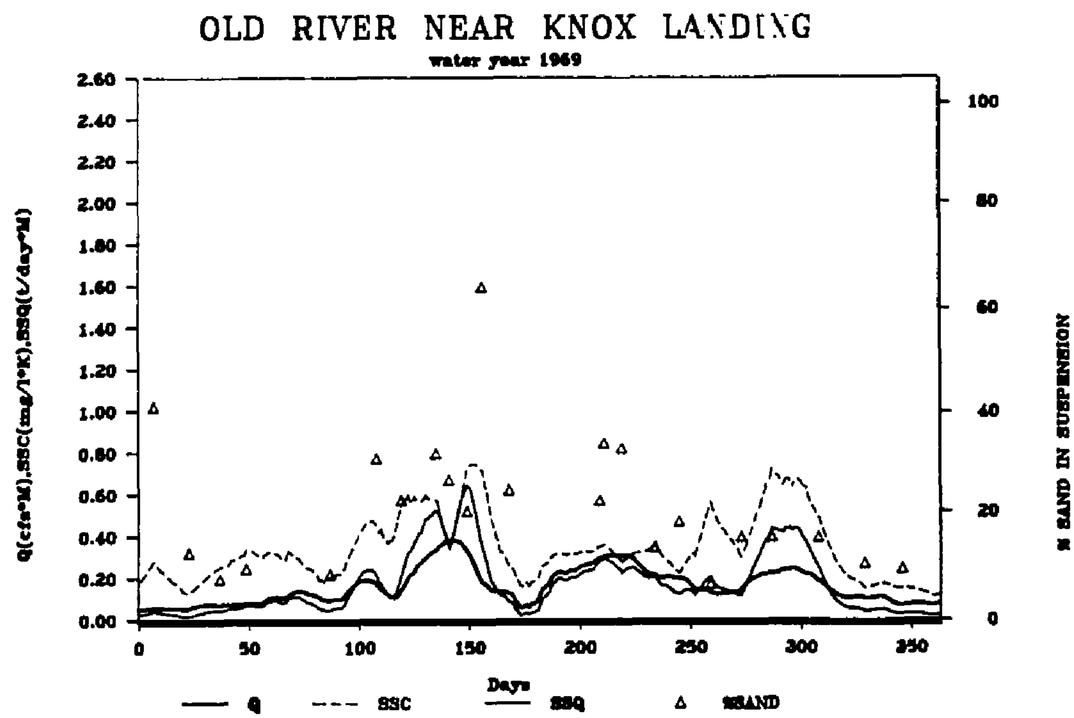
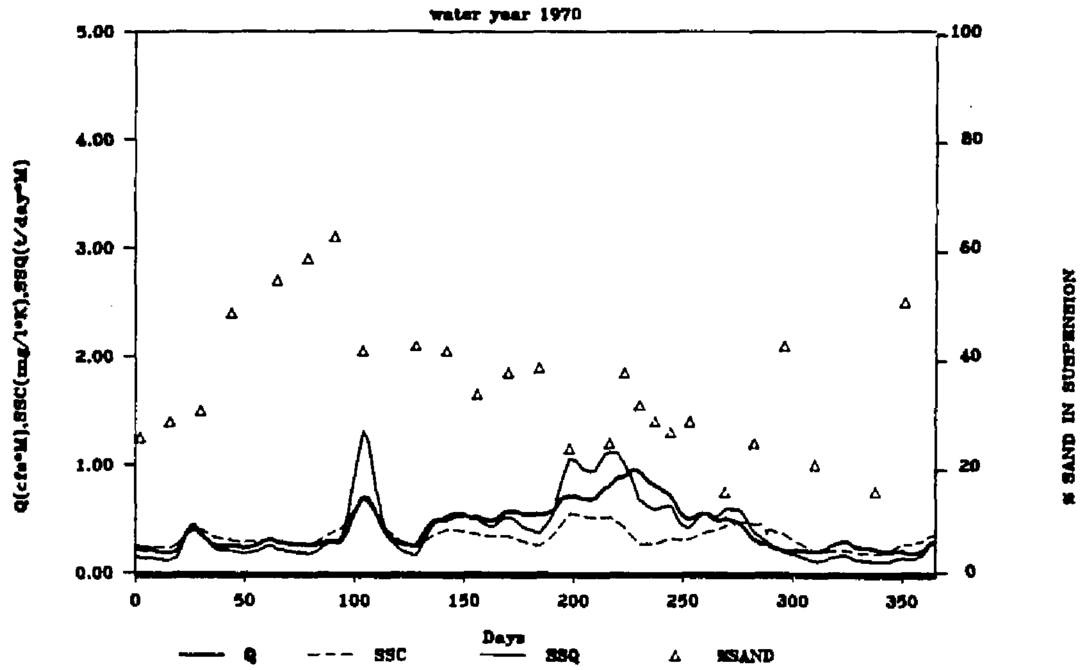


Figure A-15 (cont.). Discharge-suspended sediment relationships for water year 1969 on the Mississippi-Atchafalaya river system.

MISSISSIPPI RIVER AT TARBERT LANDING



ATCHAFALAYA RIVER AT SIMMESPORT, LA

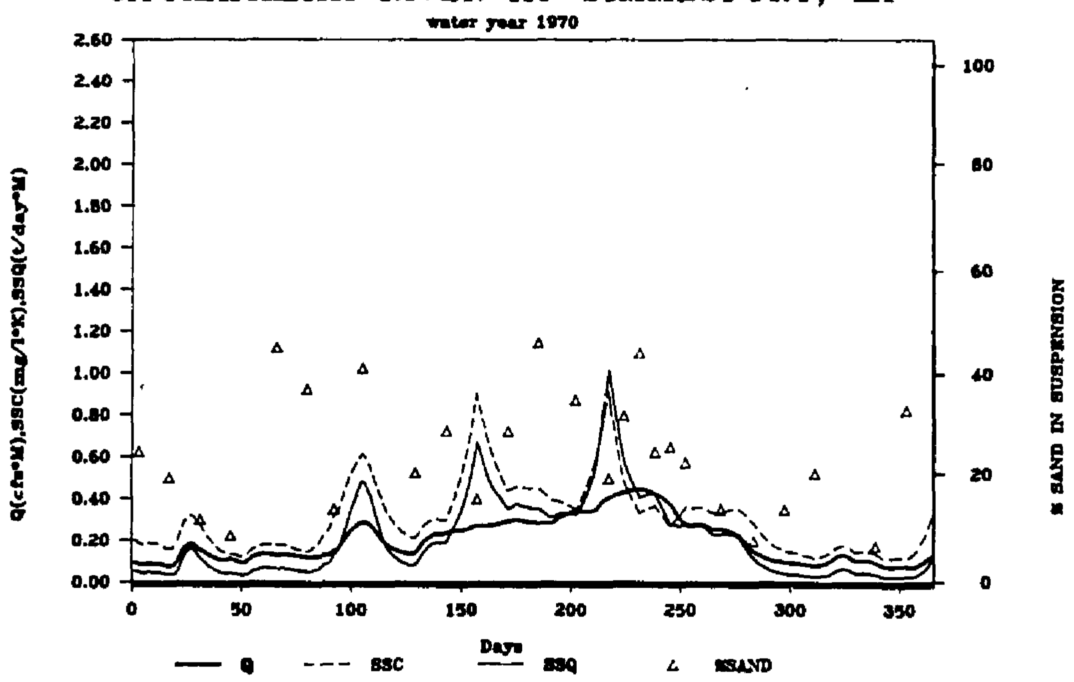
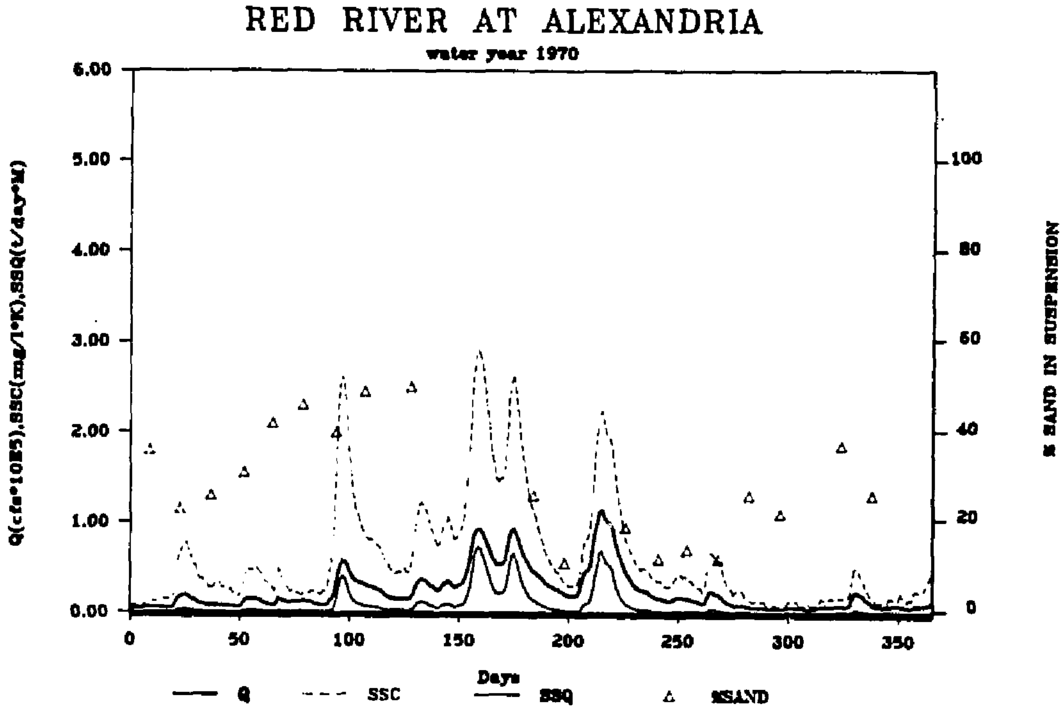


Figure A-16. Discharge-suspended sediment relationships for water year 1970 on the Mississippi-Atchafalaya river system.



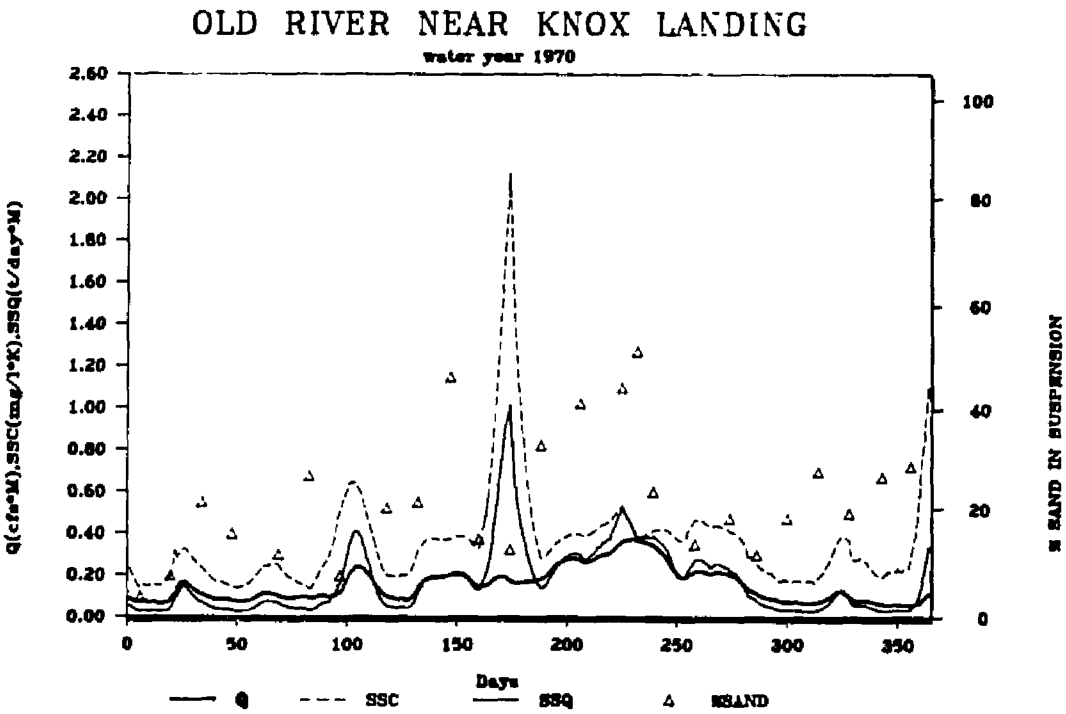
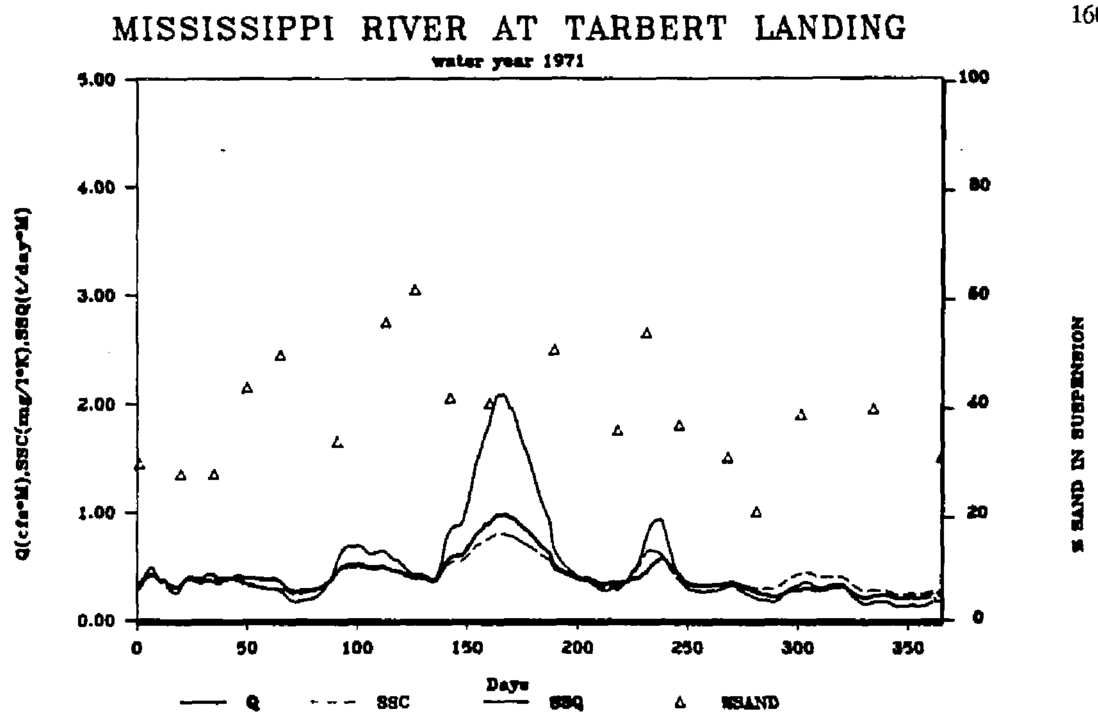


Figure A-16 (cont.). Discharge-suspended sediment relationships for water year 1970 on the Mississippi-Atchafalaya river system.



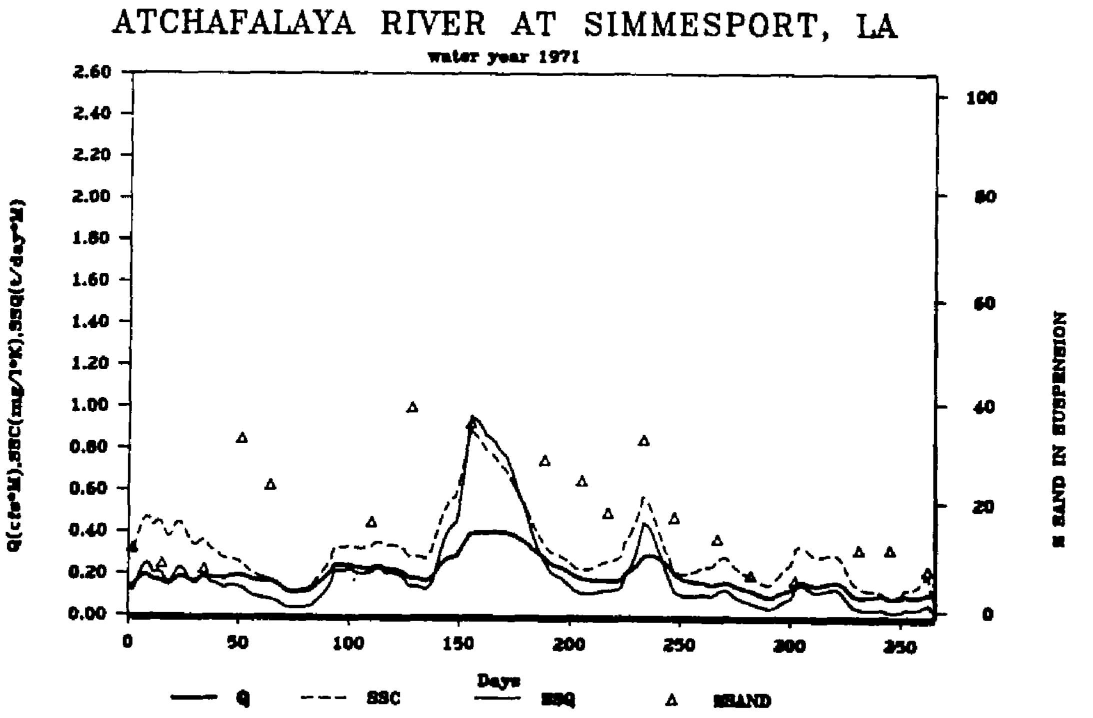
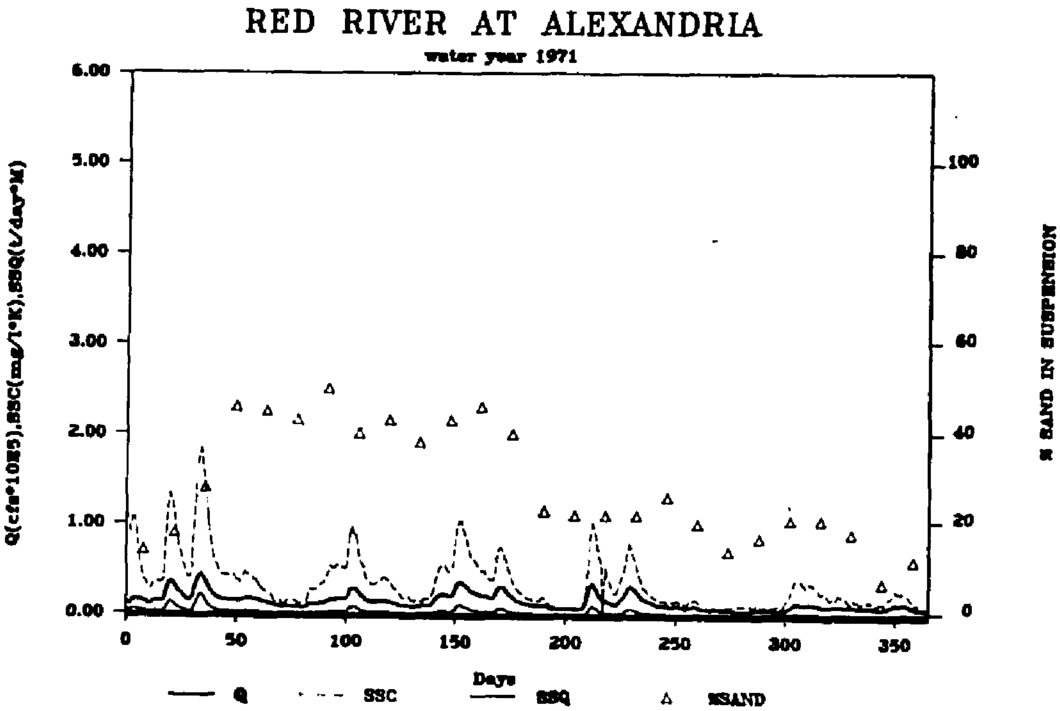


Figure A-17. Discharge-suspended sediment relationships for water year 1971 on the Mississippi-Atchafalaya river system.



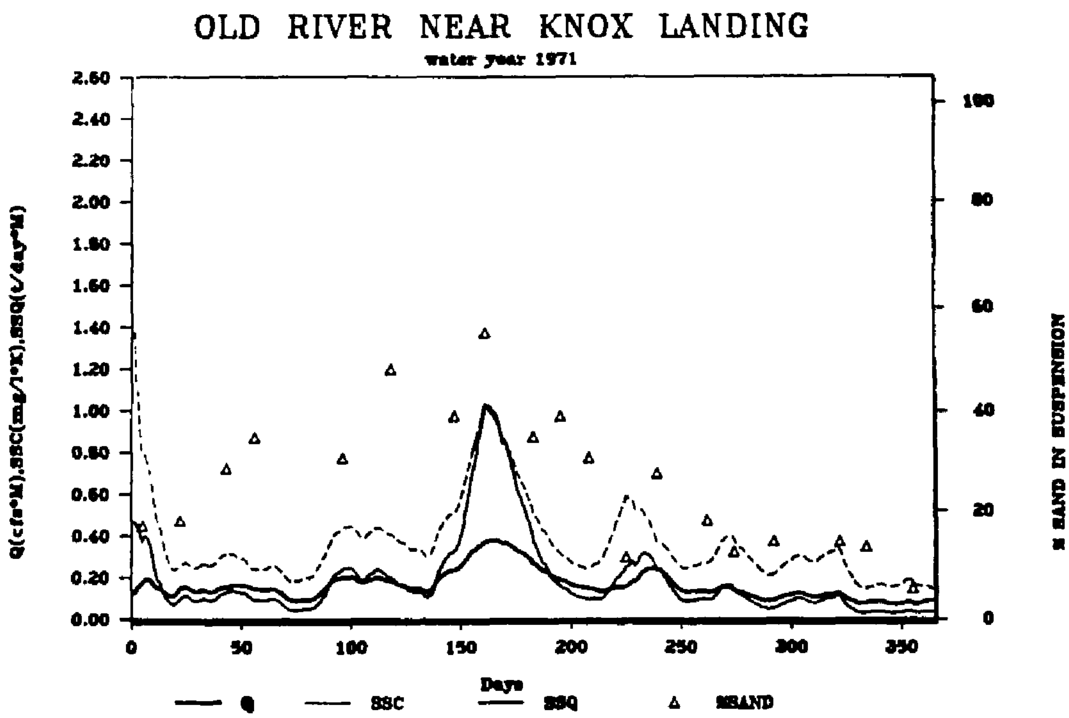
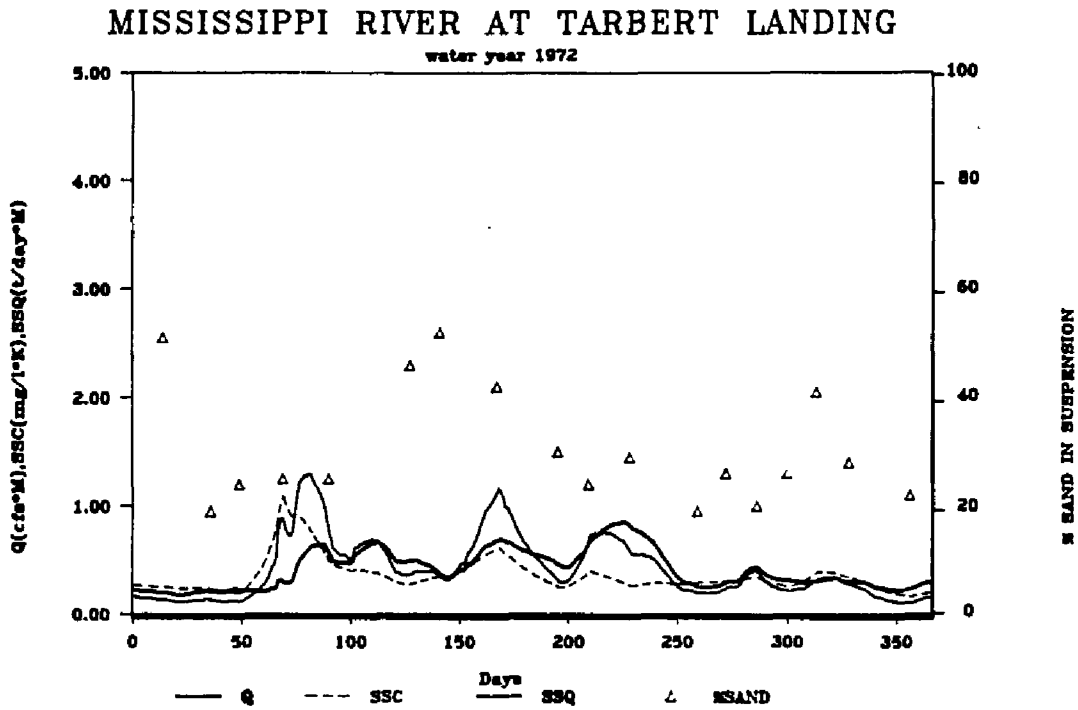


Figure A-17 (cont.). Discharge-suspended sediment relationships for water year 1971 on the Mississippi-Atchafalaya river system.



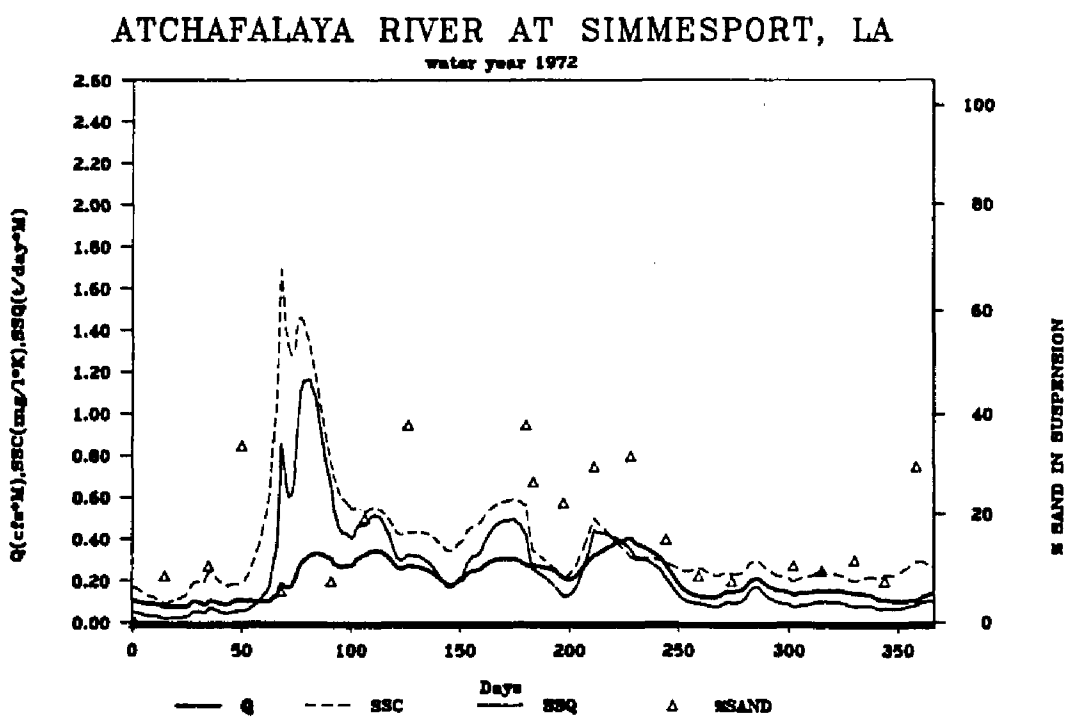
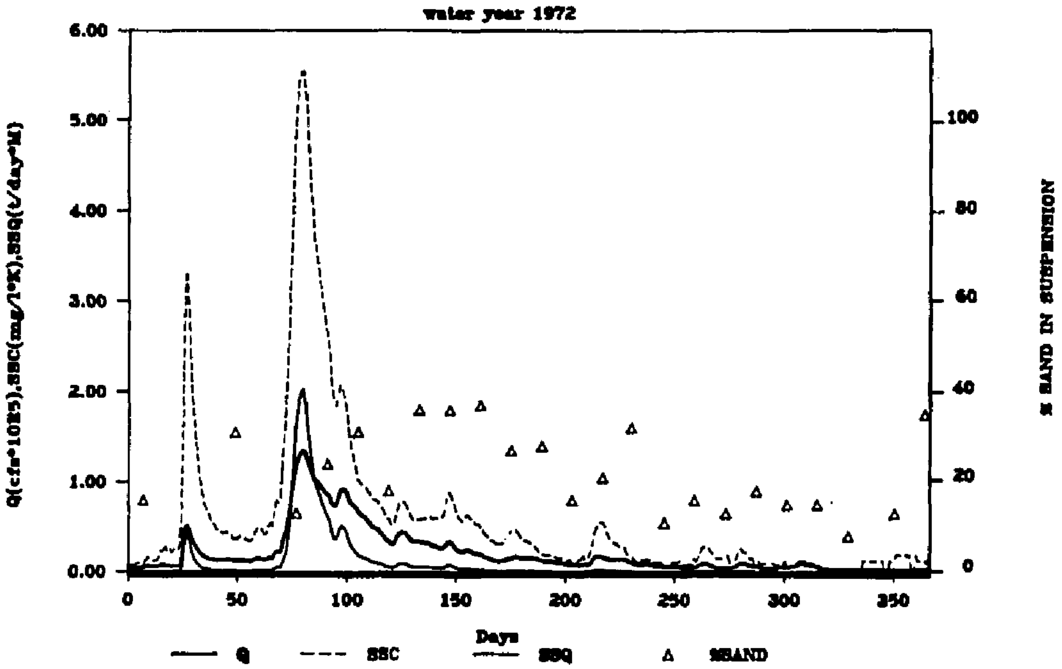


Figure A-18. Discharge-suspended sediment relationships for water year 1972 on the Mississippi-Atchafalaya river system.

RED RIVER AT ALEXANDRIA



OLD RIVER NEAR KNOX LANDING

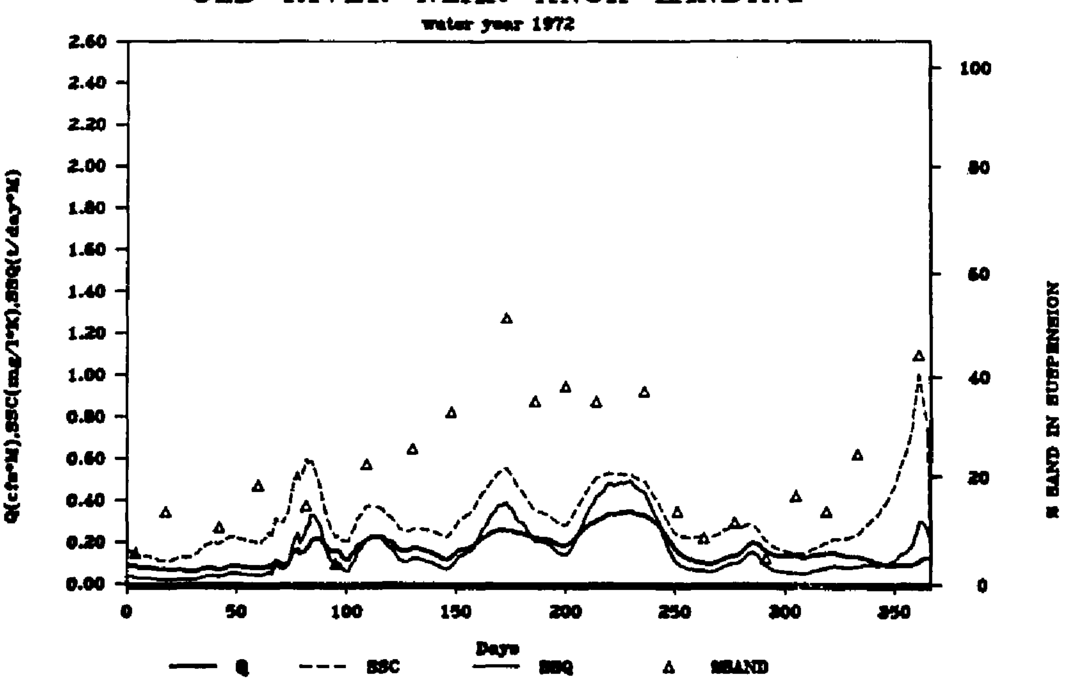
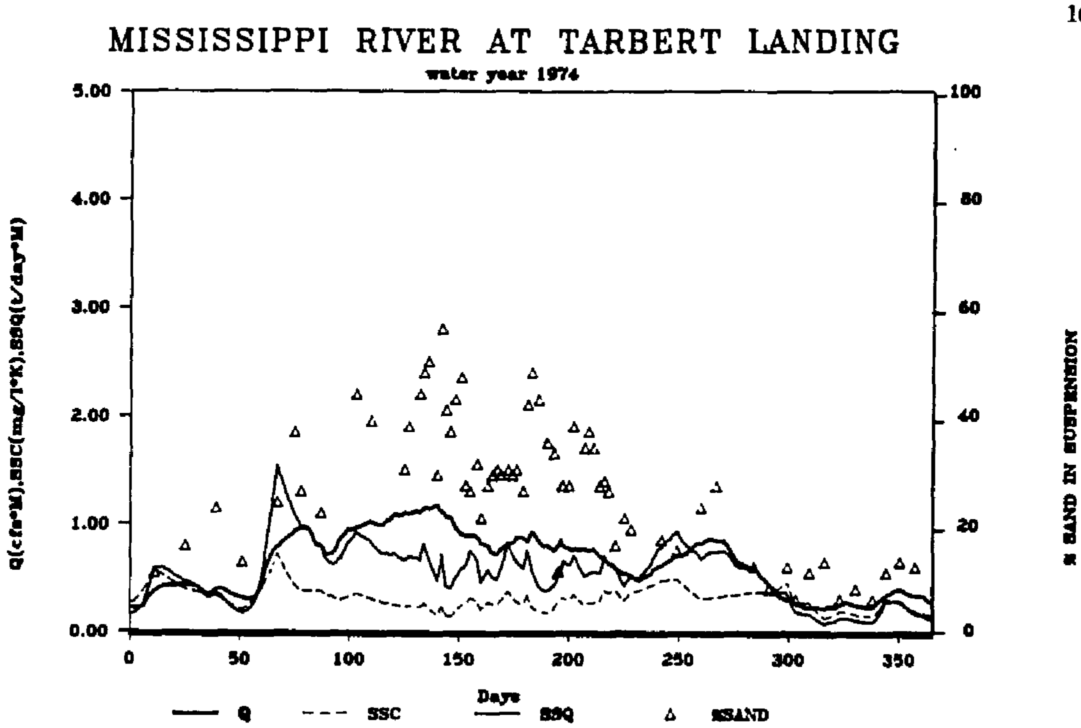


Figure A-18 (cont.). Discharge-suspended sediment relationships for water year 1972 on the Mississippi-Atchafalaya river system.



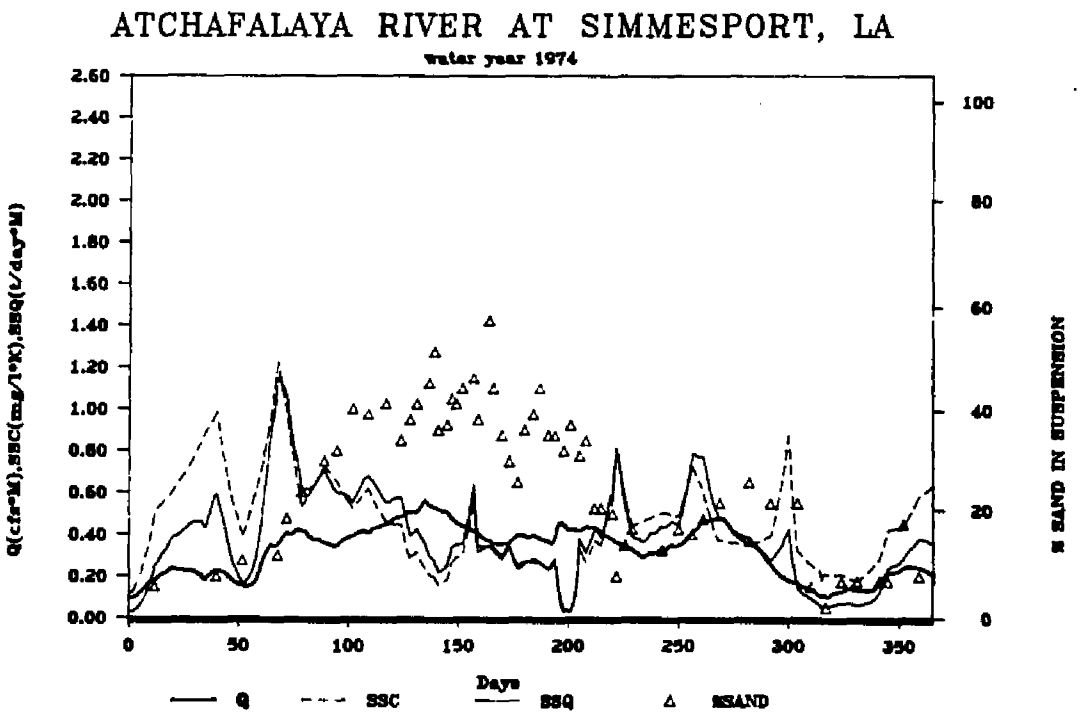
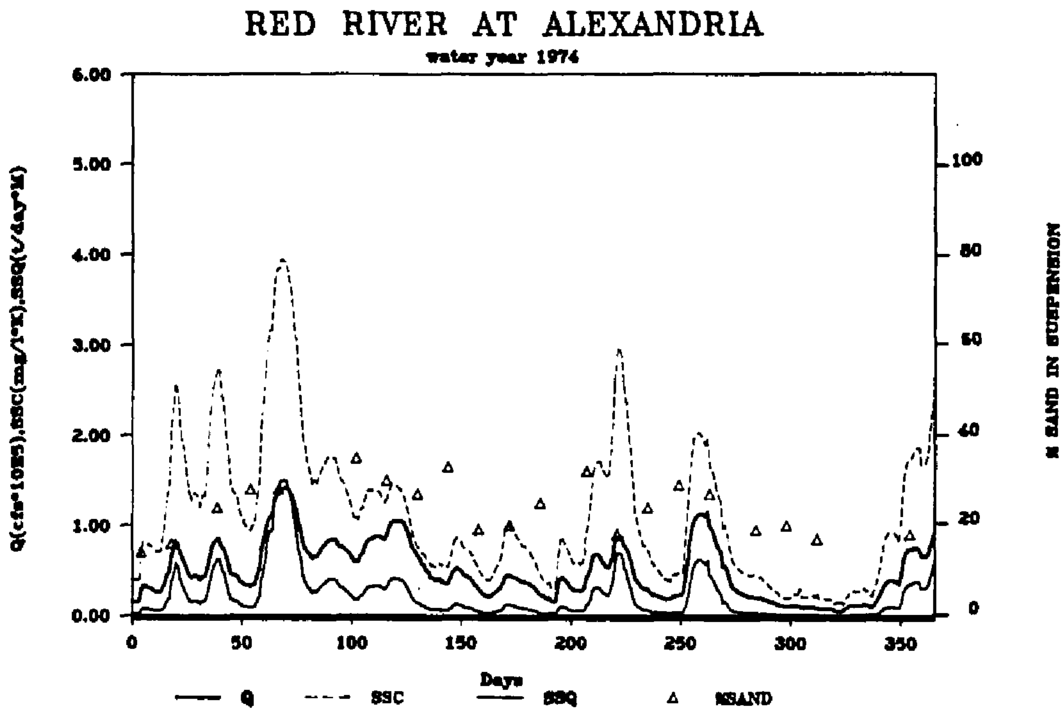


Figure A-19. Discharge-suspended sediment relationships for water year 1974 on the Mississippi-Atchafalaya river system.



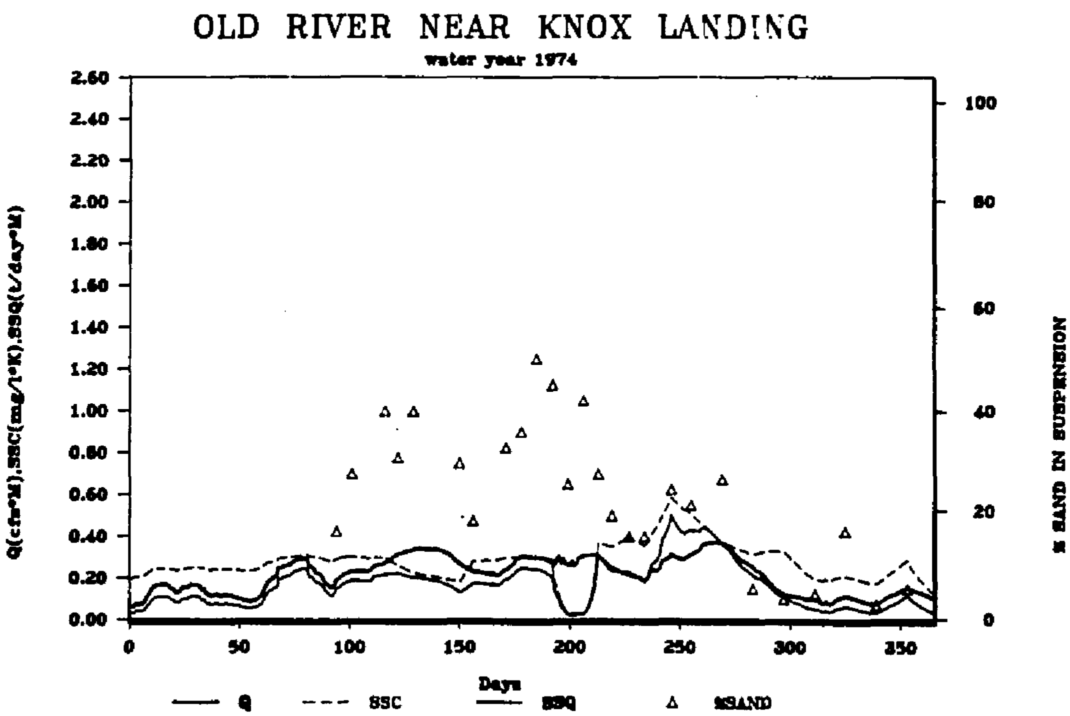
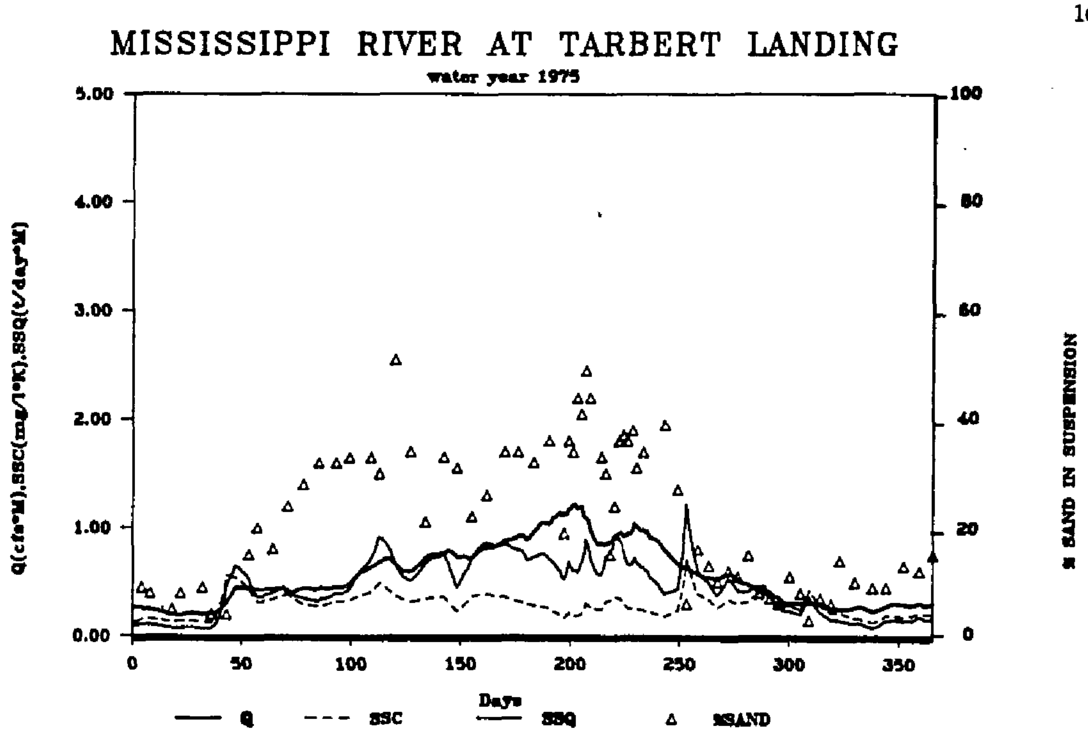


Figure A-19 (cont.). Discharge-suspended sediment relationships for water year 1974 on the Mississippi-Atchafalaya river system.



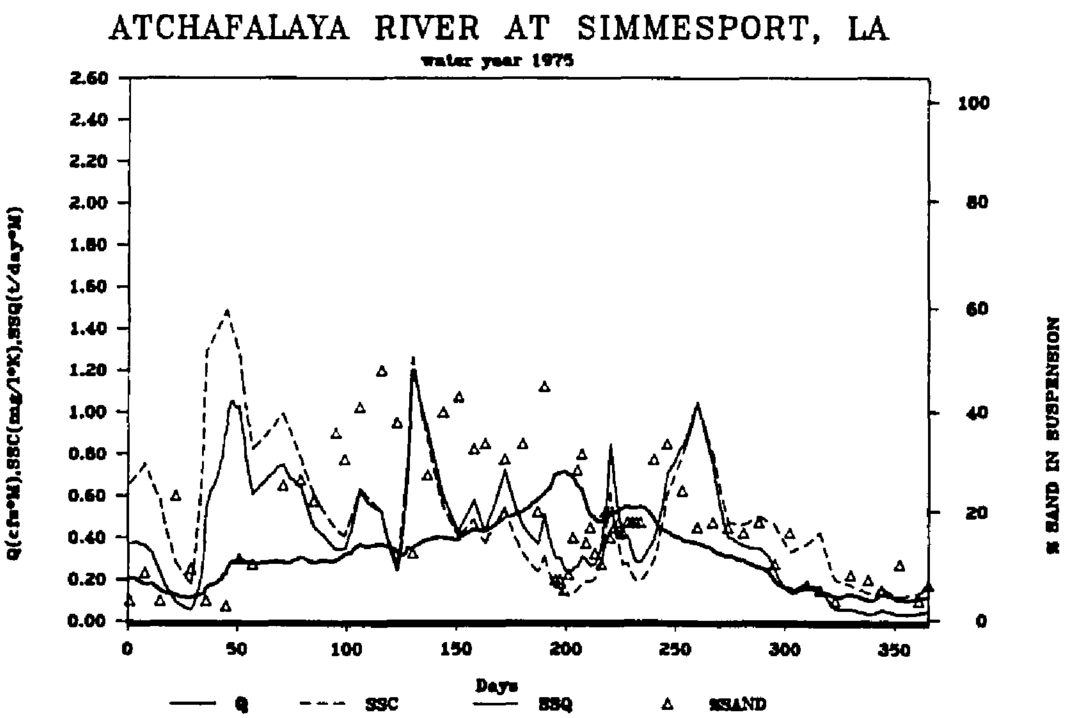
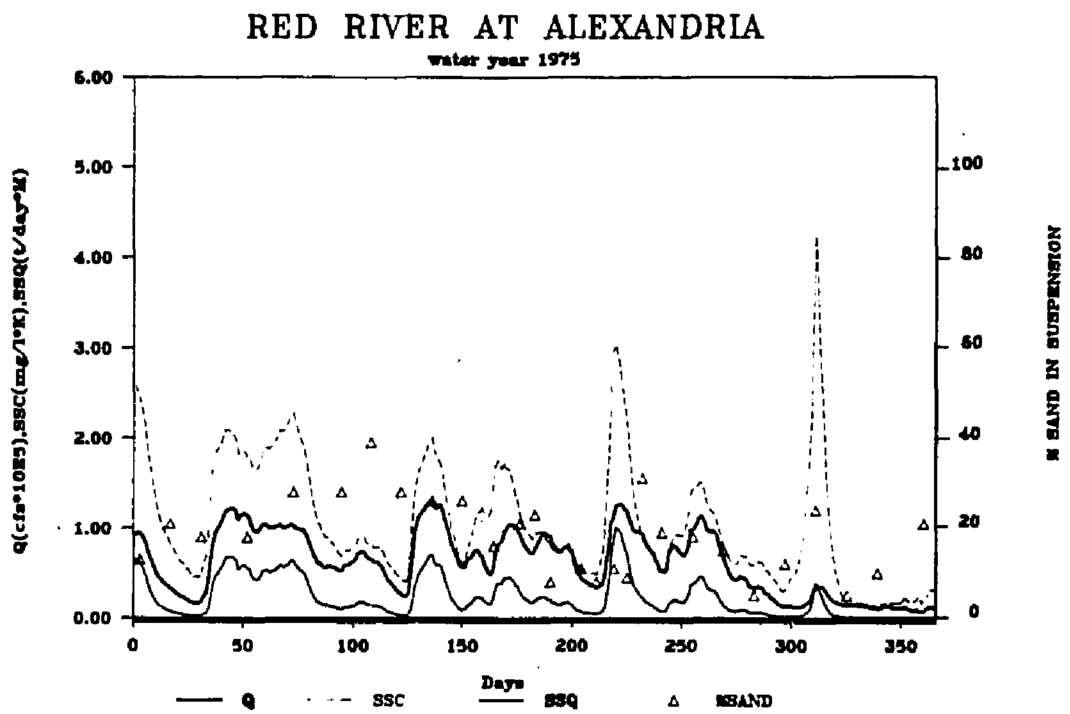


Figure A-20. Discharge-suspended sediment relationships for water year 1975 on the Mississippi-Atchafalaya river system.



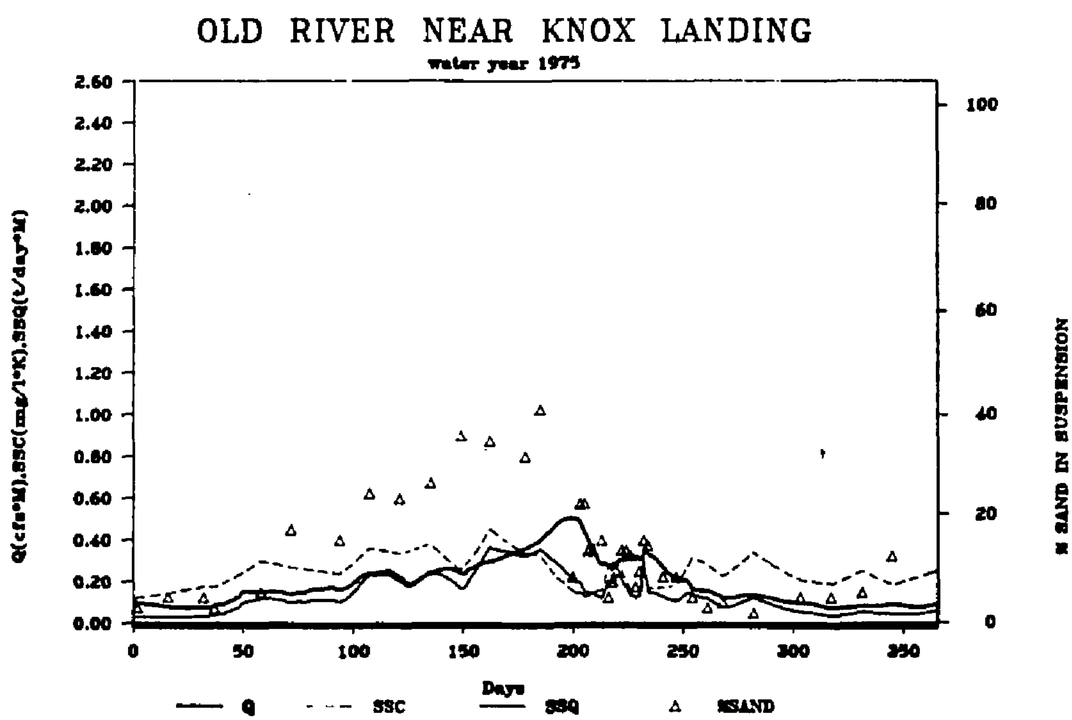
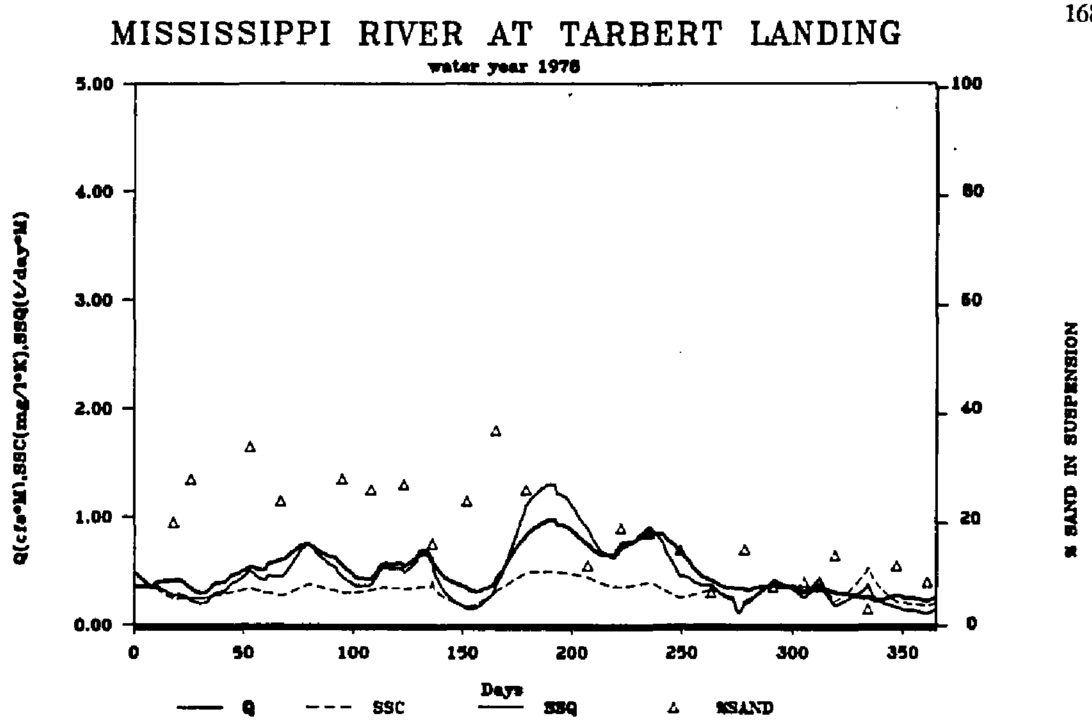


Figure A-20 (cont.). Discharge-suspended sediment relationships for water year 1975 on the Mississippi-Atchafalaya river system.



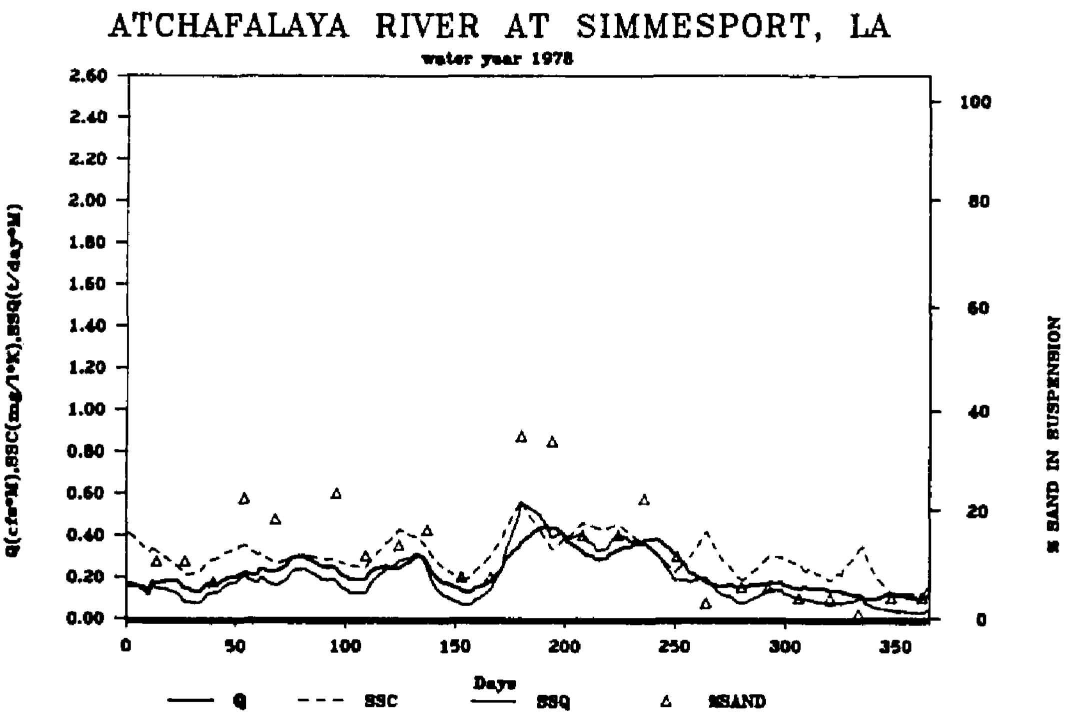
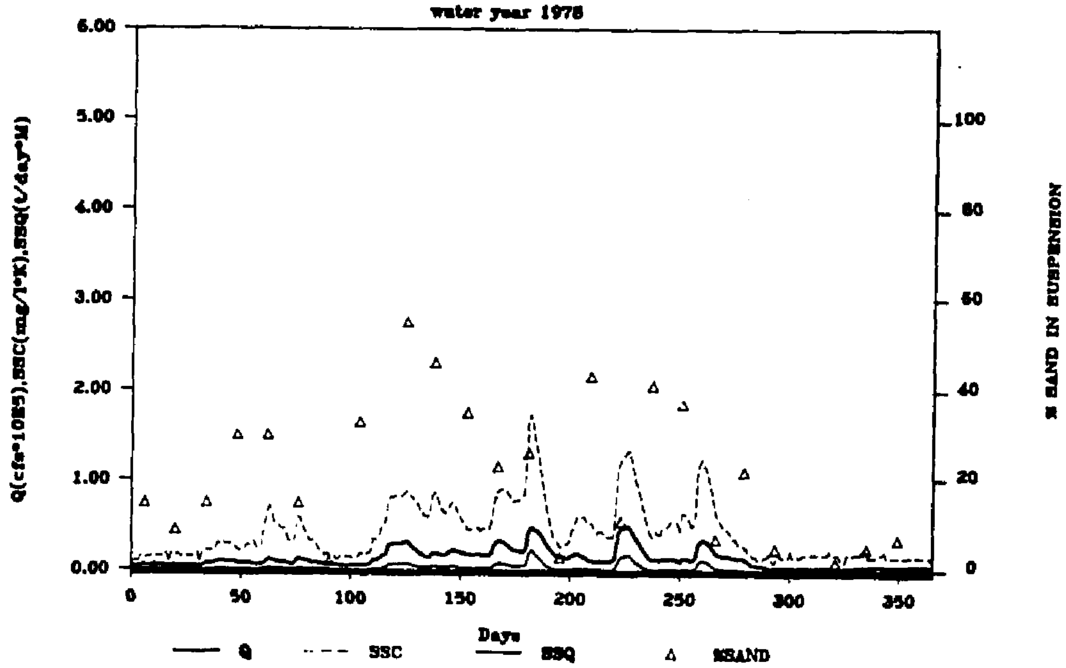


Figure A-21. Discharge-suspended sediment relationships for water year 1978 on the Mississippi-Atchafalaya river system.

RED RIVER AT ALEXANDRIA



OLD RIVER NEAR KNOX LANDING

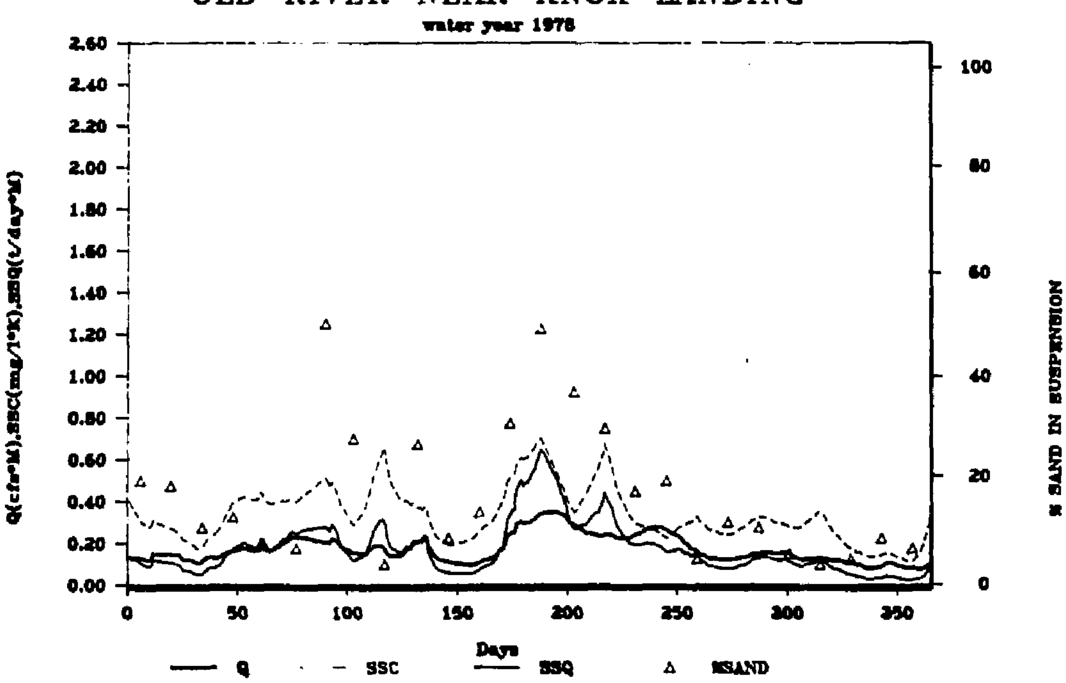
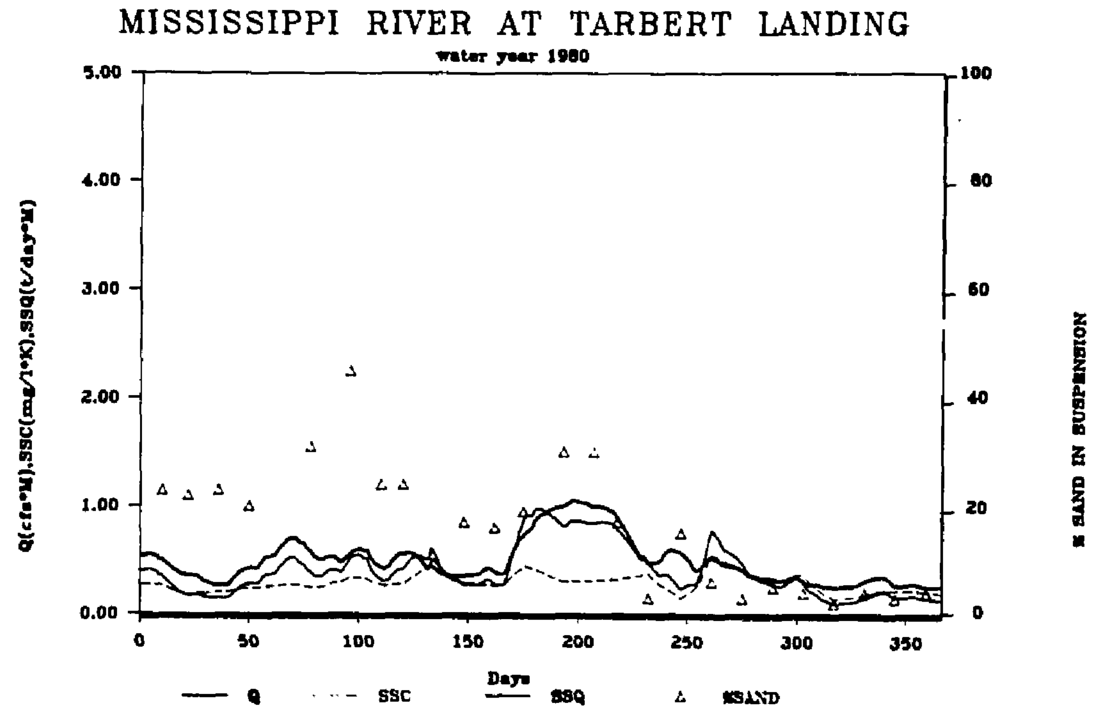


Figure A-21 (cont.). Discharge-suspended sediment relationships for water year 1978 on the Mississippi-Atchafalaya river system.



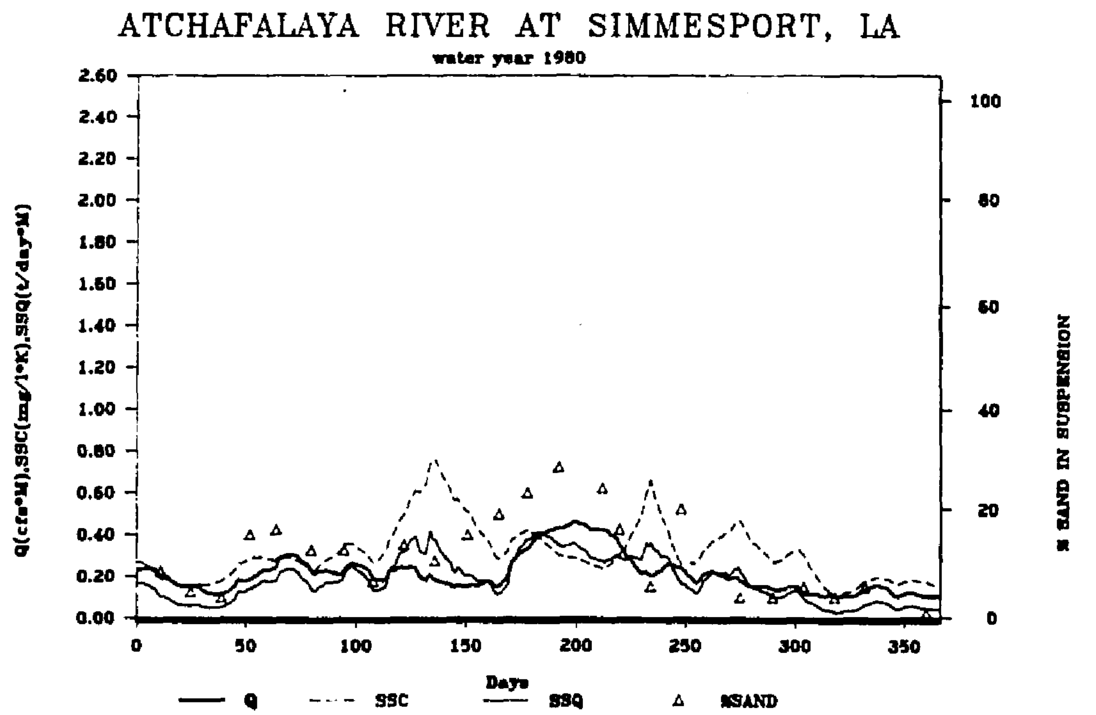
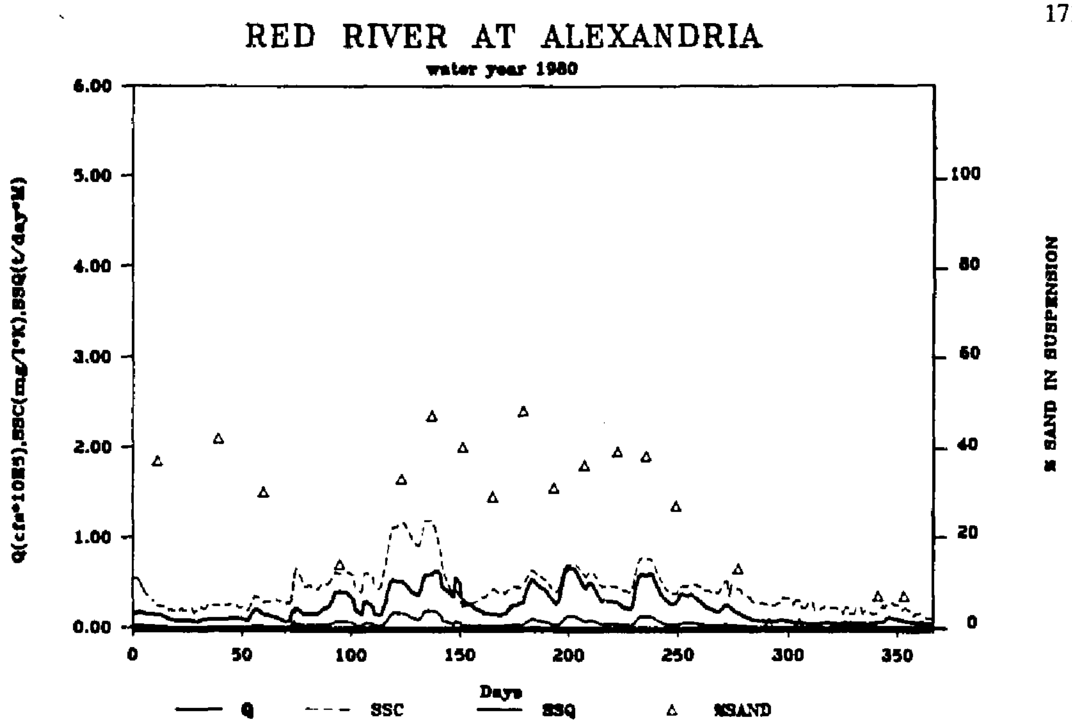


Figure A-22. Discharge-suspended sediment relationships for water year 1980 on the Mississippi-Atchafalaya river system.



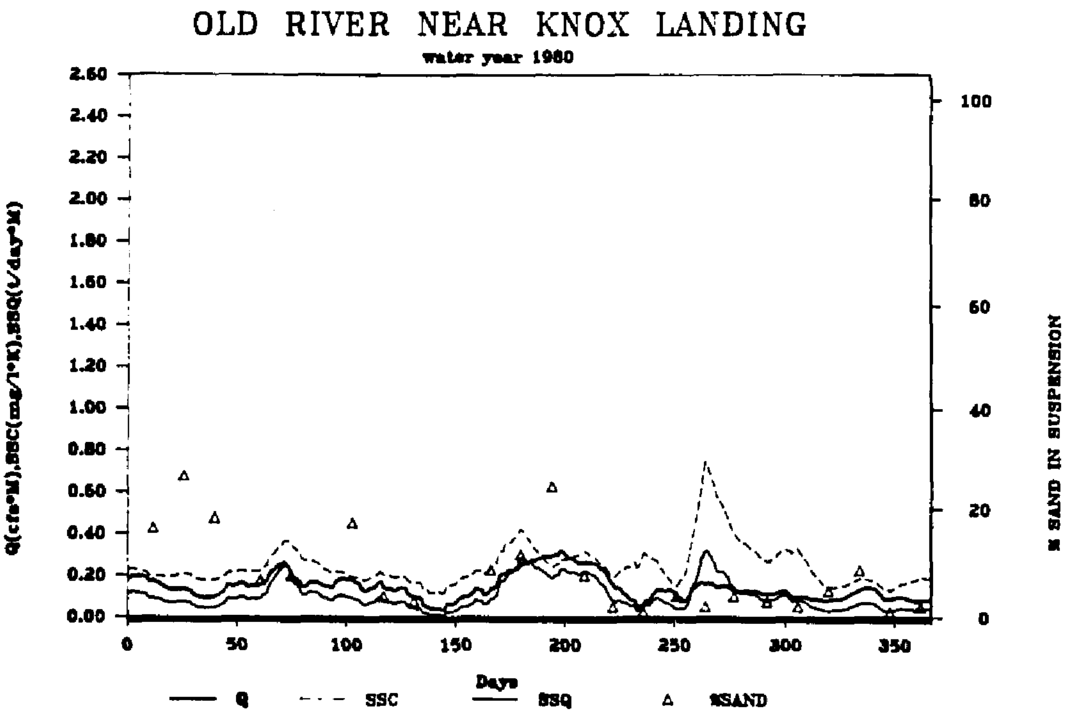
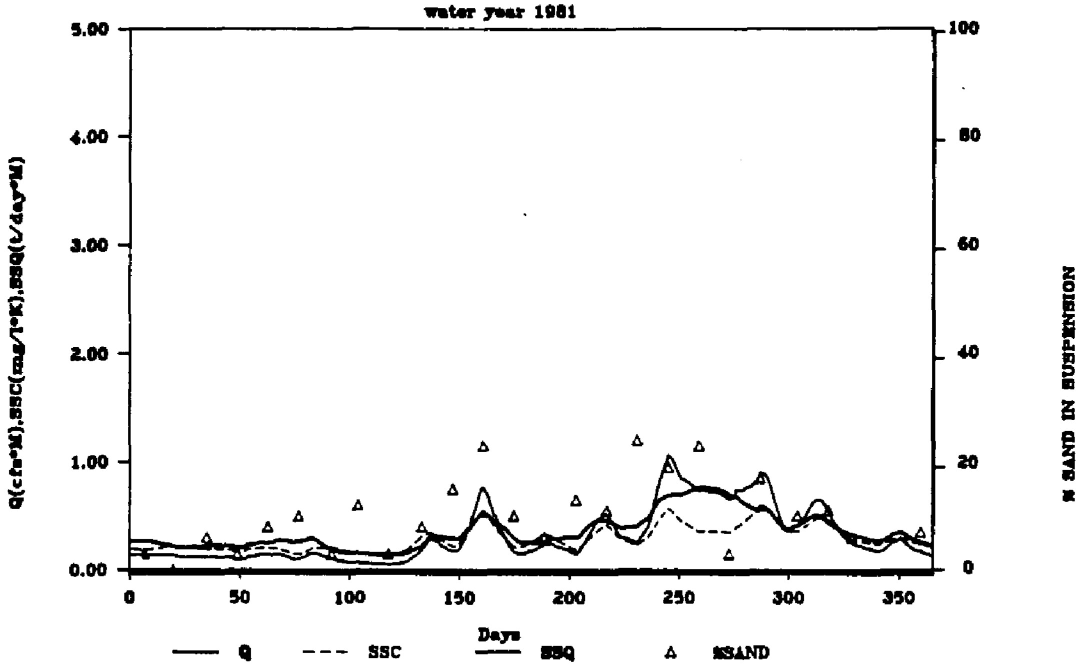


Figure A-22 (cont.). Discharge-suspended sediment relationships for water year 1980 on the Mississippi-Atchafalaya river system.

MISSISSIPPI RIVER AT TARBERT LANDING



ATCHAFALAYA RIVER AT SIMMESPORT, LA

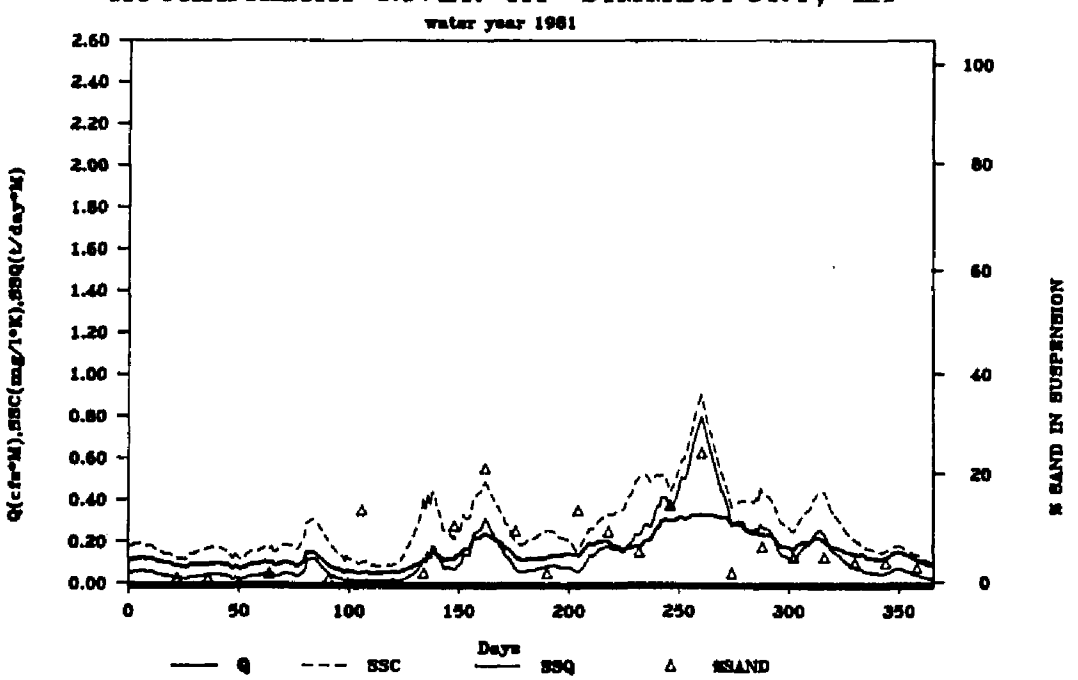
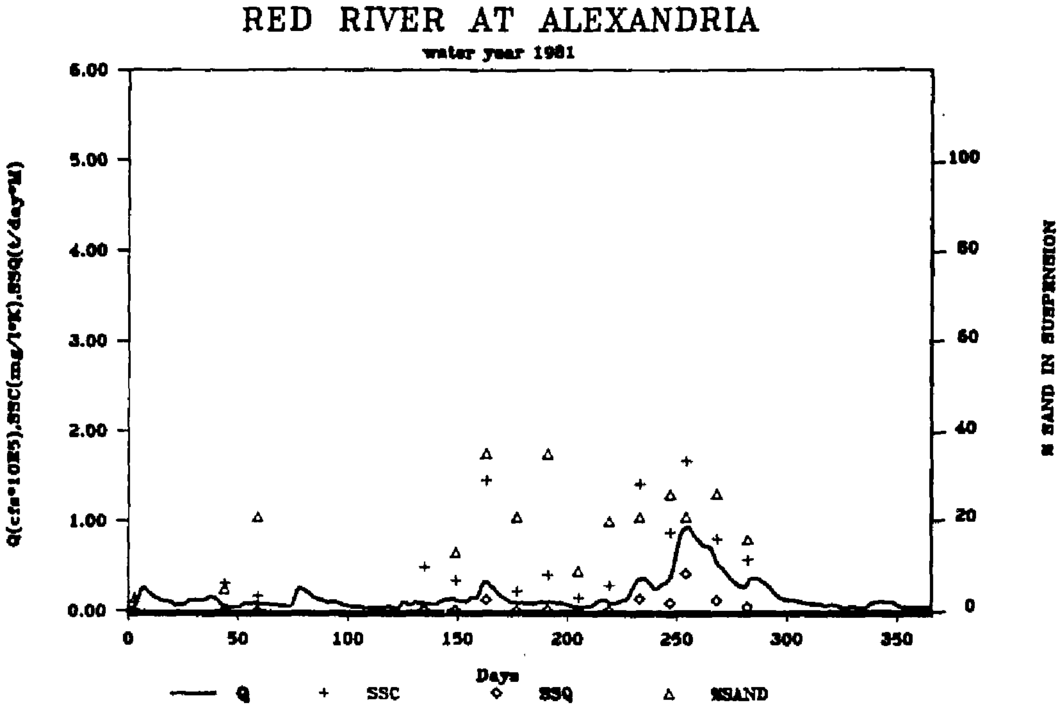


Figure A-23. Discharge-suspended sediment relationships for water year 1981 on the Mississippi-Atchafalaya river system.



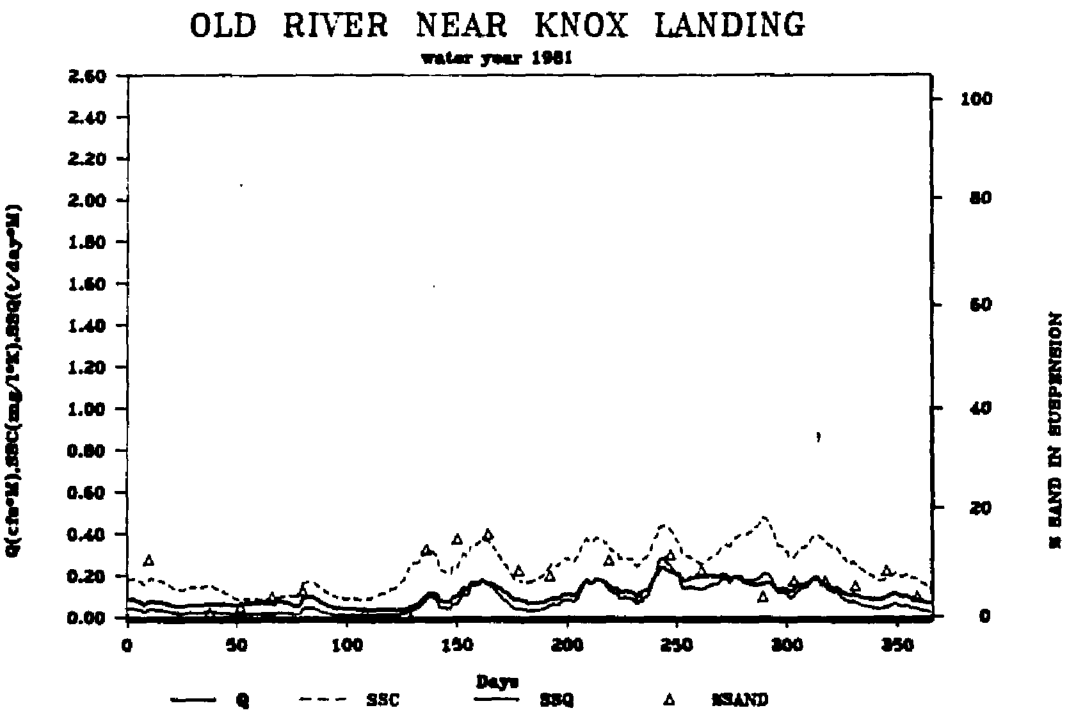
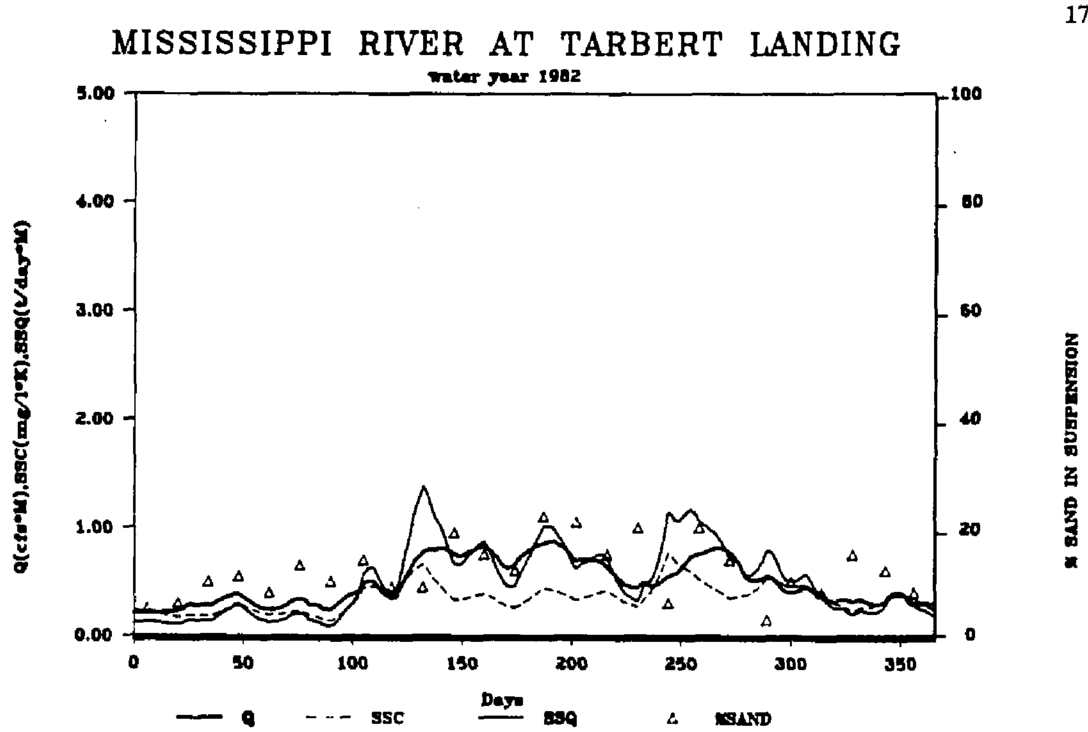


Figure A-23 (cont.). Discharge-suspended sediment relationships for water year 1981 on the Mississippi-Atchafalaya river system.



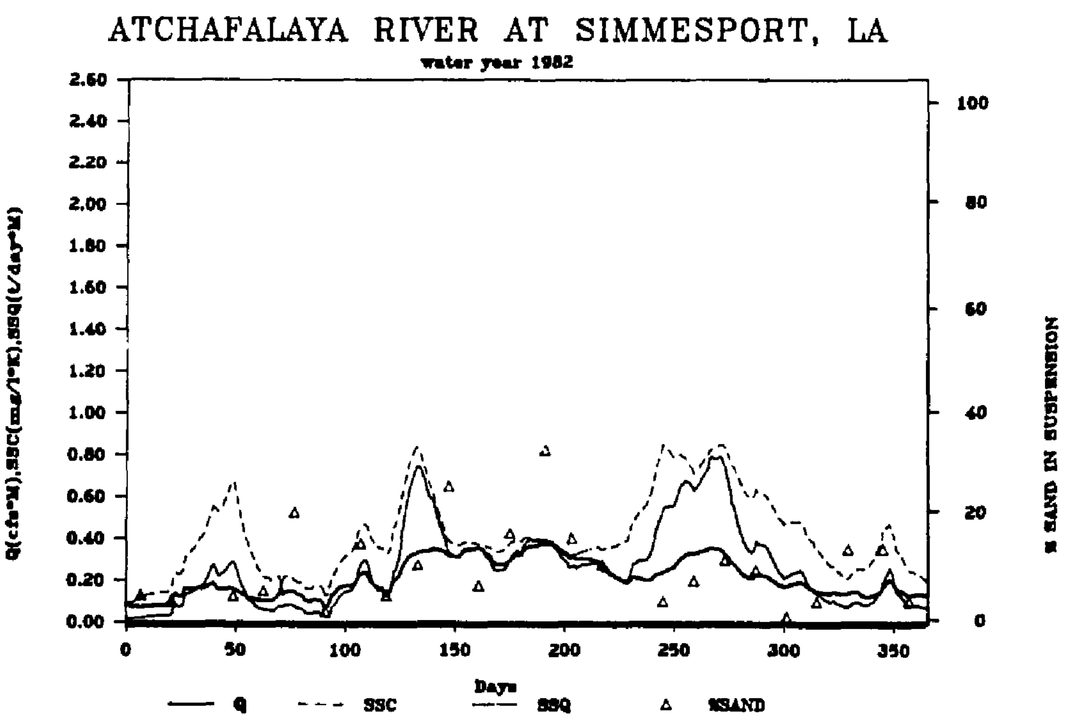


Figure A-24. Discharge-suspended sediment relationships for water year 1982 on the Mississippi-Atchafalaya river system.

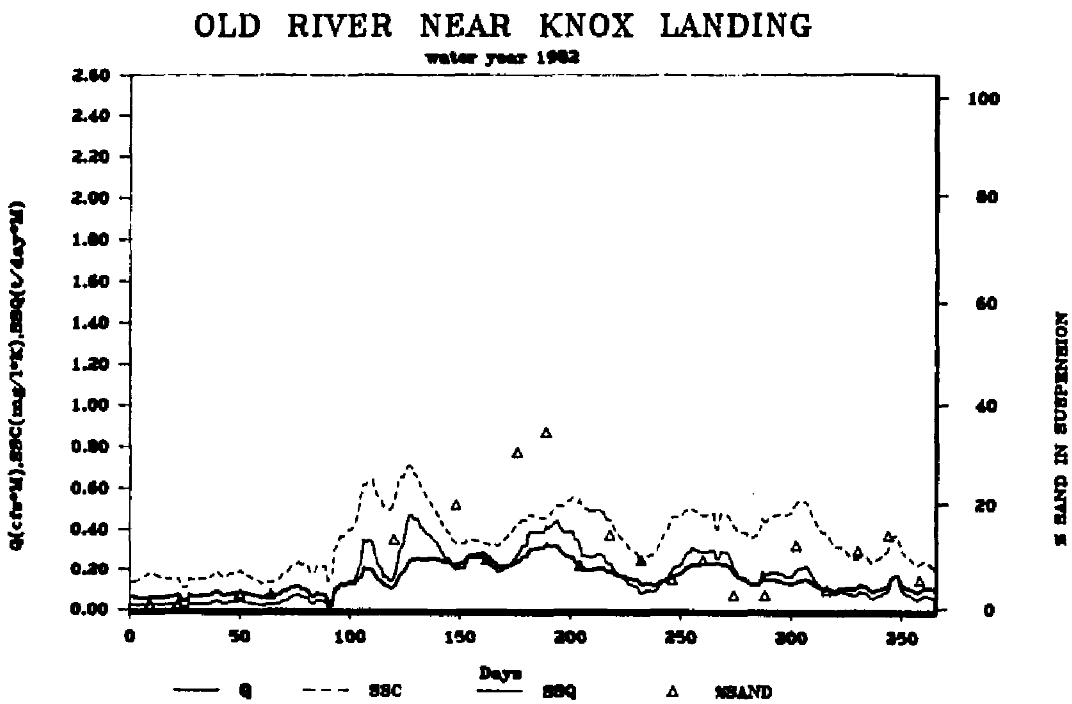
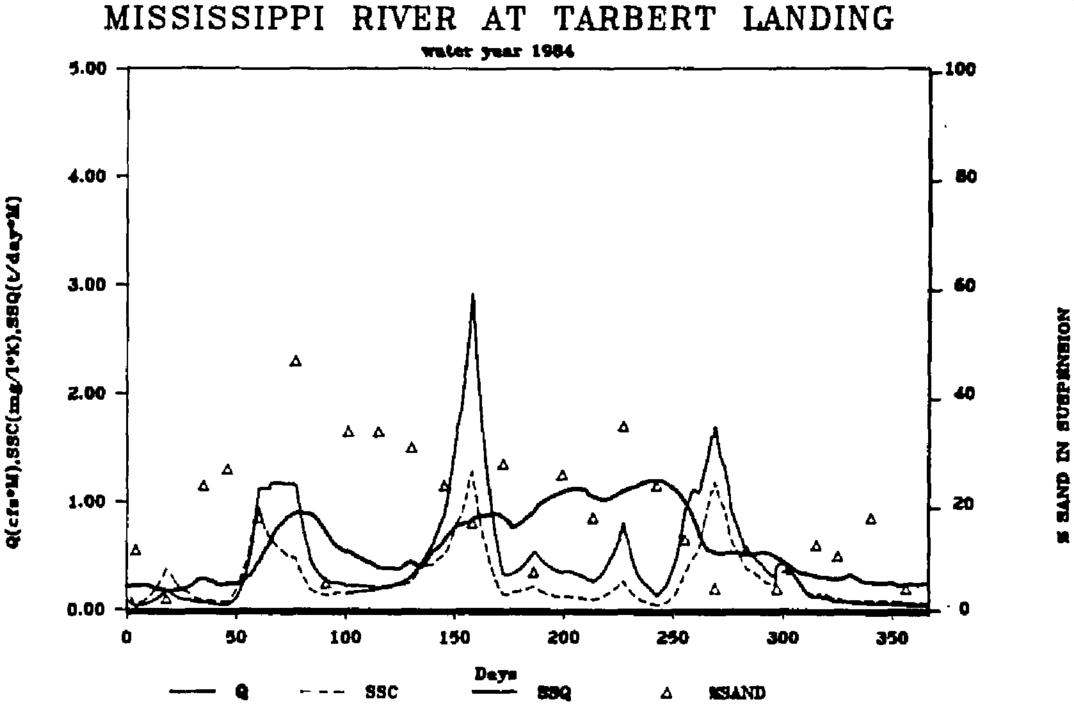


Figure A-24 (cont.). Discharge-suspended sediment relationships for water year 1982 on the Mississippi-Atchafalaya river system.



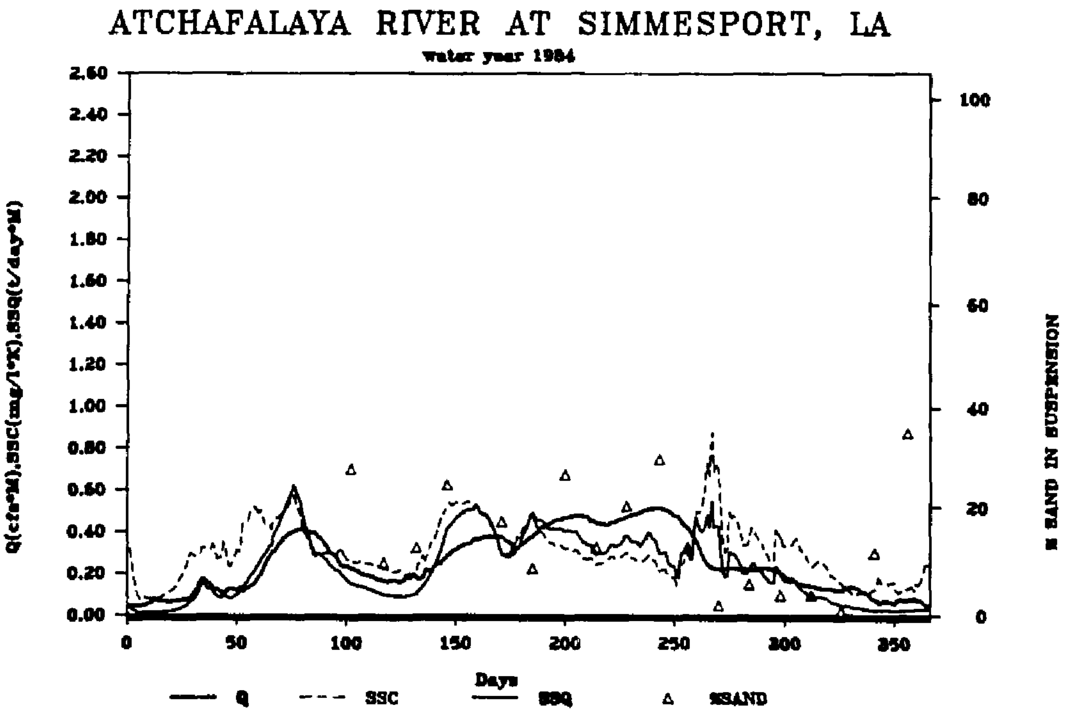


Figure A-25. Discharge-suspended sediment relationships for water year 1984 on the Mississippi-Atchafalaya river system.

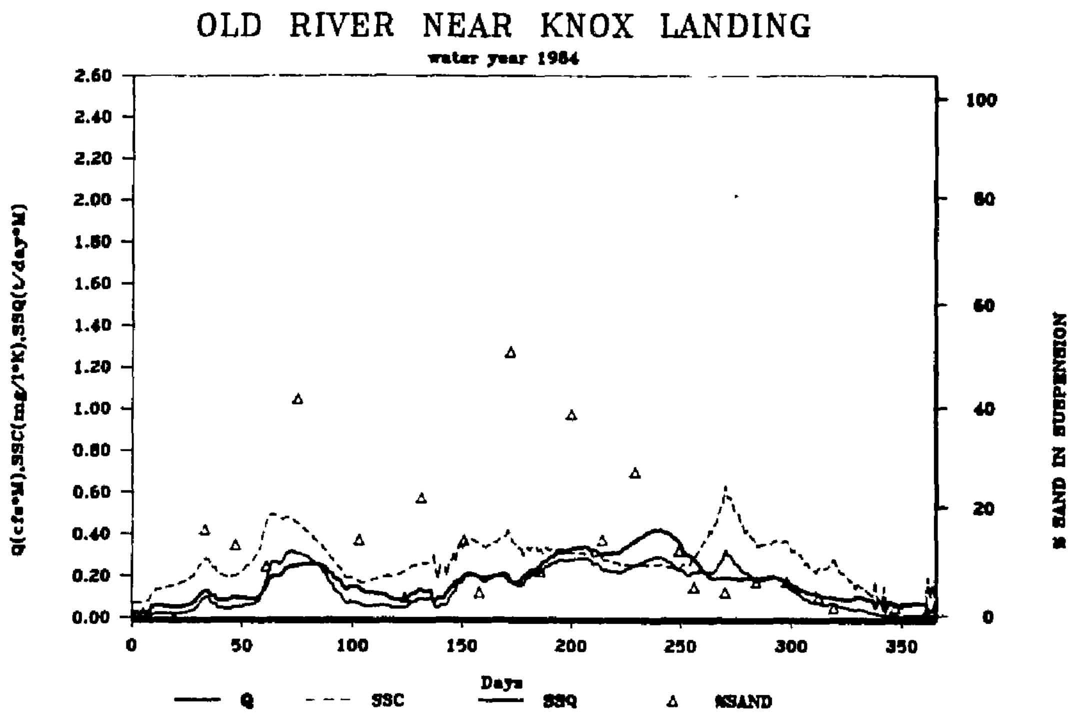
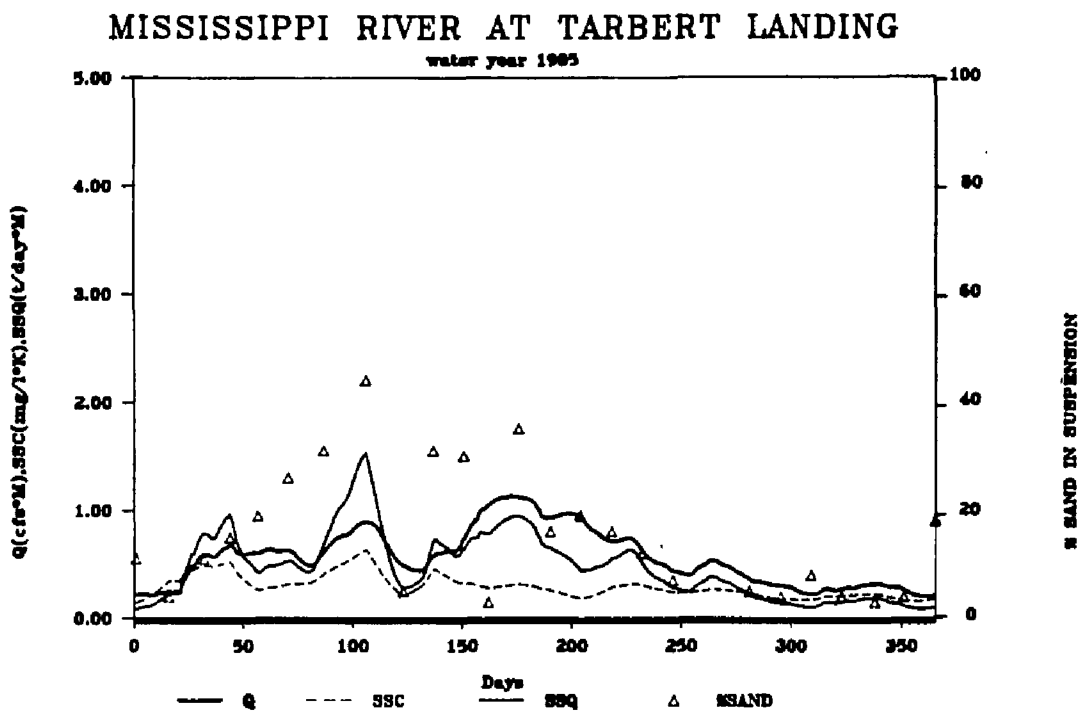


Figure A-25 (cont.). Discharge-suspended sediment relationships for water year 1984 on the Mississippi-Atchafalaya river system.



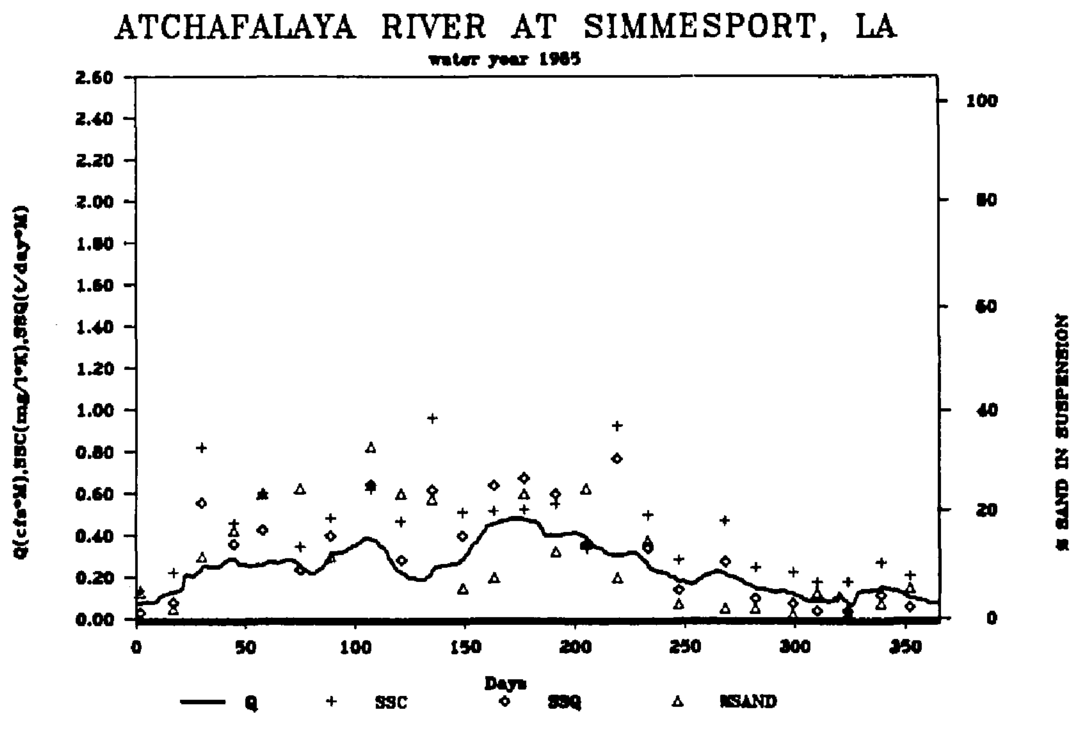


Figure A-26. Discharge-suspended sediment relationships for water year 1985 on the Mississippi-Atchafalaya river system.

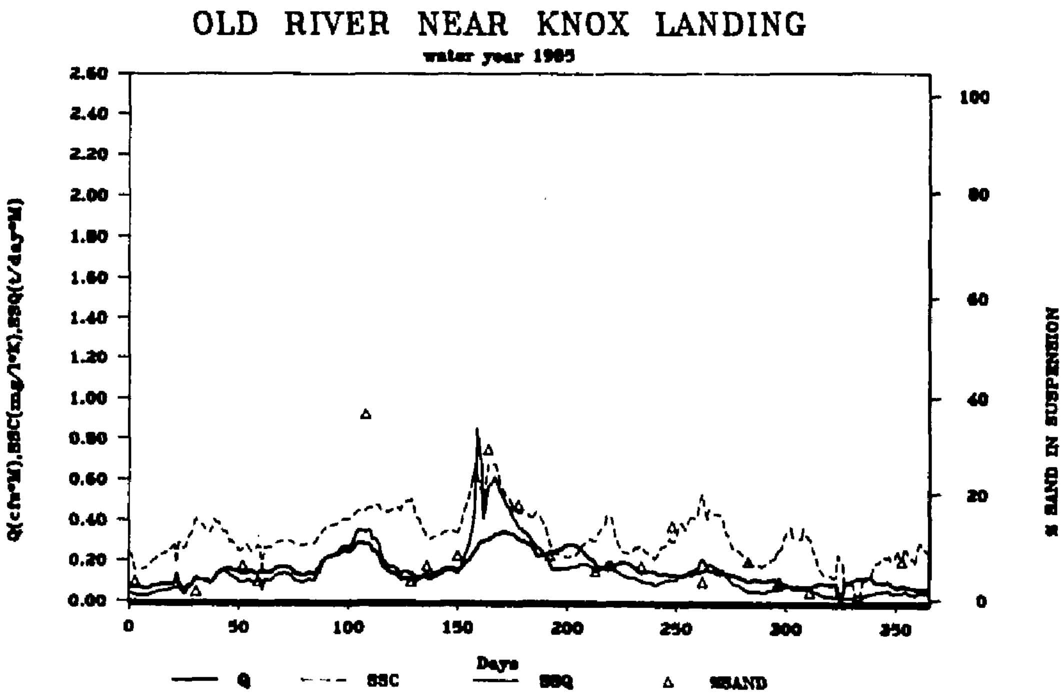


Figure A-26 (cont.). Discharge-suspended sediment relationships for water year 1985 on the Mississippi-Atchafalaya river system.

VITA

Joann Mossa was born on October 28, 1959 in Summit, New Jersey. She grew up on the terminal moraine in the Precambrian highlands in Rockaway Township, and graduated from Morris Knolls High School in Denville, New Jersey in 1976. In May 1980, she graduated Phi Beta Kappa with a B.A. in both Geography and Mathematics from Rutgers College of Rutgers University in New Brunswick, New Jersey, on the piedmont. After graduating, she toured Europe and then moved to low-lying Mississippi Valley and Pleistocene terraces in Baton Rouge, Louisiana, where she began studies in August 1980 towards a M.S. degree in Geography at Louisiana State University. While working on her degree, she was employed at Louisiana State University as a Graduate Assistant and Research Assistant in the Department of Geography and Anthropology and at the Remote Sensing and Image Processing Laboratory, as an Instructor in the Department of Mathematics, and as a Research Associate with the Louisiana Geological Survey. She completed her degree under the supervision of H. Jesse Walker in December 1983 on periglacial geomorphology and remote sensing in the North Slope of Alaska. She continued to work with the Louisiana Geological Survey, conducting geomorphic research in coastal, fluvial, and Quaternary environments in Louisiana, where she received grants and contracts from several state and federal agencies. While working, she entered the Ph.D. program in Geography on a part-time basis, with interdisciplinary coursework emphasizing fluvial geomorphology and soils. Following completion of her Ph.D., she will be employed as an Assistant Professor in the Department of Geography at the University of Florida in Gainesville, surrounded by sinkholes and springs.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Joann Mossa

Major Field: Geography

Title of Dissertation: Discharge-Suspended Sediment Relationships in the Mississippi-Atchafalaya River System, Louisiana

Approved:

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